(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 026 068 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
09.08.2000 Bulletin 2000/32

(51) Int. Cl.⁷: B62D 15/02

(21) Application number: 00300847.1

(22) Date of filing: 03.02.2000

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 05.02.1999 GB 9902438

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(54) Improvements relating to electric power assisted steering systems

(57) An electric power assisted steering system (1) is disclosed which comprises a steering shaft (2) connected at one end to the handwheel (2) and at its other end to at least one roadwheel (4), whilst an electric motor (6) is connected to the steering shaft (2) through a gearbox (7) having a non-integer reduction gear ratio. Two sensors (9;8,10) are also provided with one (9) sensing the angular position of the motor rotor and the other (8,10) sensing the angular position of the steering shaft (2). The presence of the non-integer gear ratio produces a beat frequency between the output of the two sensors (9;8,10) from which an unambiguous measurement of the angular position of the steering shaft (2) over a range of greater than one complete revolution can be made. The sensors (9;8,10) may comprise either absolute position sensors or index-type sensors.

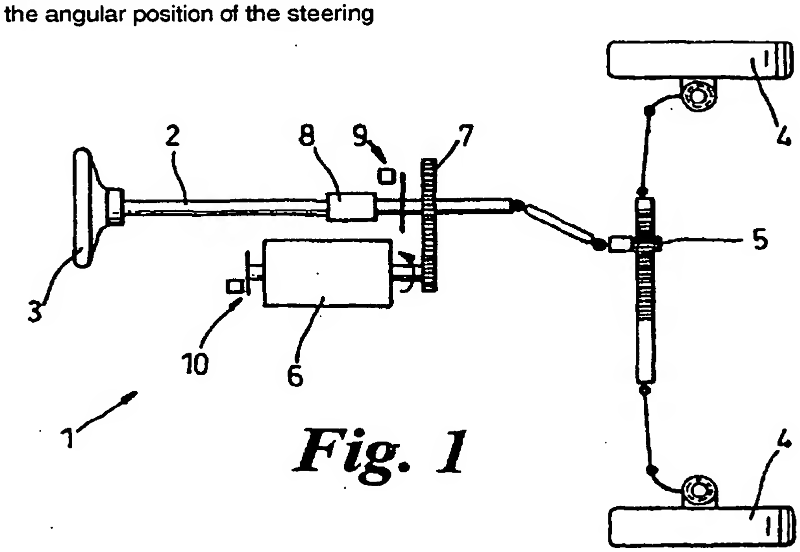

Fig. 1

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Description

[0001] This invention relates to improvements in electrical power assisted steering systems, and in particular to an improved apparatus for measuring the absolute steering angle of the road wheels.

[0002] Typical electric power assisted steering systems comprise a steering shaft operatively connected at a first end to a steering wheel and at its opposite end operatively connected to the roadwheels of a vehicle. An electric motor is provided which can apply torque to the steering shaft through a reduction gearbox. The gearbox may be of the worm and wheel, or other, type.

[0003] A steering gear is provided between the steering shaft and the steered wheels. This steering gear typically provides a substantial gearing between angular movement of the steering shaft (and hence hand wheel) and the movement of the roadwheels. For a typical road vehicle, more than one turn of the handwheel (i.e. complete revolution of the steering shaft) is needed to move the roadwheels from lock to lock.

[0004] It is desirable to be able to measure the steering angle of the roadwheels. This can be used to influence a number of sub-systems in the vehicle such as suspension damper control systems, vehicle stability control systems and vehicle lane guidance.

[0005] One solution to the problem would be to provide an angular position sensor on the steering shaft to measure the angle of rotation of the steering shaft. However, as more than one full revolution is needed to turn from lock to lock such a measurement would not unambiguously describe the angle of the roadwheels.

[0006] The problem of measuring multiple turns of the steering shaft can be overcome in several ways, each with its own disadvantage.

[0007] In one proposal, the steering shaft angular position sensor can be driven by the steering shaft through a step down gear, reducing the total number of turns of the sensor to less than one full revolution. This overcomes the problem of ambiguity, but unfortunately reduces the resolution which can be obtained from the sensor. To produce a high resolution system is therefore expensive.

[0008] According to the present invention, we provide an electric power assisted steering system comprising: a steering shaft operatively connected at a first end to a handwheel and at its other end operatively connected to at least one roadwheel, an electric motor having a rotor operatively connected to the steering shaft through a gearbox having a non-integer reduction gear ratio, a first sensing means adapted to produce an output dependent on the angular position of the steering shaft; a second sensing means adapted to produce an output dependent on the angular position of the rotor, and processing means adapted to process both output signals to produce an angular position signal indicative of the angular position of the steering shaft over a range of greater than one complete revolution.

[0009] The invention thus employs outputs from two sensors, one monitoring the position of the steering shaft and the other monitoring the position of the motor rotor to provide, if desired, an unambiguous measurement of steering shaft angle over a range of angles in excess of one full revolution.

[0010] Preferably, both sensors are adapted to produce a cyclic output signal dependent upon angular position which repeats after a complete revolution, or perhaps a fraction of a full revolution. The cycle may repeat upon a complete rotation of the associated steering shaft or motor rotor, i.e. 1 cycle corresponds to 360° of rotation. For example, one sensor may produce an absolute angular position value which varies substantially linearly over the range 0-360 degrees of rotation between a value of 0 and 1. The sensor will therefore produce the same output value for shaft or rotor positions of 90°, 90°+360°, 90°+720° etc. Alternatively, it may have a range of 0-180°, and thus the cycle will repeat itself once within a single revolution.

[0011] At least one of the sensors may comprise an absolute angular position sensor. By this we mean that the sensor produces a signal that represents the absolute angular position of the shaft or rotor within a complete revolution (or part of a revolution). Examples of sensors of this kind include potentiometers, a resolver, a synchro and an optical angle encoder. For clarity, it is assumed that the absolute sensor produces an output that varies substantially linearly between 0 and 1 over its range of output values.

[0012] Alternatively, at least one of the sensors may comprise an index sensor. By this we mean a sensor which is adapted to produce an output signal dependent on angle which is indicative of the position of the shaft within a small fraction of a revolution. Such a sensor may, for example produce a short pulse as the shaft rotates past its index position, and zero output in all other positions. Again, more than one index pulse may be produced within a single revolution, i.e. two equal-spaced pulses per complete revolution.

[0013] Preferably, the sensors are driven directly from the steering shaft or motor rotor without intermediate gearing. Thus, with a sensor having a cycle of 360 degrees, for one turn of the shaft the sensor measures one full revolution.

[0014] Preferably, the gear ratio may be expressed as p/q whereby the motor turns through p/q revolutions for each revolution of the steering shaft, p is greater than q, q is greater than unity, and the greatest common integer factor of p and q is also unity.

[0015] By gearbox ratio, we mean the ratio between the rotation of the two sensors. Thus, if each sensor produces an output value over a range corresponding to one full revolution, the gear ratio is the turns ratio between the input side

and output side of the gearbox. If one sensor produces an output which cycles or repeats n times within one revolution of its respective shaft or rotor, the gearbox ratio will be np'/q where np'=p as herein before.

[0016] By selecting a non-integer ratio, the outputs of the two sensors will drift out of synchronisation as the steering shaft rotates. Eventually, after a predetermined number of revolutions, the output will return into synchronisation. This "beating" enables an unambiguous measurement of rotation over a range greater than one revolution to be achieved from sensors which produce an output over a range of one revolution or less.

[0017] In one arrangement, the first sensing means comprises an absolute handwheel position sensor and the second sensing means comprises an index sensor adapted to produce an index signal at a known angular position of the motor rotor, said processing means being adapted to sample the output of the first sensing means corresponding to the position when the second sensing means produces an index signal;

multiply the sampled value by p;

round the multiplied value to the nearest integer to produce a reference value and

use the reference value to access the corresponding entry in a look-up table, said entry being indicative of the number of revolutions of the steering shaft from an arbitrary zero position..

[0018] In another arrangement, the first sensing means may comprise an index sensor adapted to produce an index signal at a known angular position of the handwheel with the second sensing means comprising an absolute position sensor.

[0019] In yet a further alternative, both sensing means may comprise absolute position sensors. Again, the processing means is adapted to exploit the way in which the outputs of the sensors drift out of synchronisation and back into synchronisation after a number of revolutions to obtain a measure of the number of rotations of the steering shaft from an arbitrary zero angular position. A benefit of using two absolute position sensors is that it is no longer necessary to wait until one of the sensors passes an index, allowing a more regular estimate of position to be made.

[0020] In the event that both sensors comprise absolute position sensors, the processing means may be adapted to estimate the angular position of the motor rotor from a measurement of the angular position of the steering shaft assuming it is on its "zero" revolution. This estimate may then be compared with the actual output signal from the second sensing means, and the difference between the estimate and actual values processed to produce a signal indicative of the number of revolutions of the steering shaft relative to an arbitrary zero angular position.

[0021] The processing means may therefore, in one system, be adapted to multiply the measured steering shaft position value output from the first sensing means by the gear ratio p/q to produce a predicted motor shaft position, sample the actual motor position from the second sensing means, compare the predicted value to the actual measured steering position, calculate the difference between the measured value and predicted value, and process the difference value to produce a value indicative of the number of turns of the steering shaft.

[0022] The processing means may be further adapted to calculate a residue of the difference and multiply the residue by q. This multiplied value may then be rounded off to the nearest integer, and the rounded value used to access a look-up table.

[0023] It is envisaged that the apparatus can be modified in a number of ways. For example, the second sensing means may in one arrangement comprise a number of Hall effect sensors adapted to detect the angular position of one or more magnets on the motor rotor.

[0024] In a most preferred arrangement, the motor may comprise a brushless permanent magnet motor and the motor sensor may comprise a number of Hall effect sensors adapted to detect the position of the magnetic poles. Three sensors may be provided for a three phase motor. This allows a resolution of $1/6^{th}$ of an electrical revolution of the rotor. For instance, with a 3 phase motor with 6 poles, the output will repeat 3 times for one whole revolution of the motor rotor.

[0025] The second sensing means may also be used to provide position information for use by a motor control circuit. For example, it can be used to calculate the timing for motor commutation events.

[0026] In accordance with a second aspect, the invention provides an electric power assisted steering system comprising a steering shaft operatively connected to one or more roadwheels and an electric motor adapted to apply an assistance torque to the shaft which incorporates a means adapted to check the relationship between the actual angular position of the steering angle and the expected angular position of the road wheel carriers.

[0027] The straight ahead position will vary in service. Specifically, the relationship between the angle or linear position of the steering system components may change due to wear or deformation of the chassis components, adjustment of the steering or suspension components or the replacement of steering system components. By checking the relationship between actual and measured angle such changes can be detected and compensated or corrected as necessary.

[0028] The measured angular position of the steering shaft may be produced using an electric power assisted

steering system which embodies the first aspect of the invention.

[0029] It is envisaged that there are several preferred ways of achieving the checks by recognising that the vehicle is travelling in a straight line which are described below. Any number of these can be combined to detect if the vehicle is travelling in a straight line. If the methods detect that the absolute steering angle does not correspond with the straight-ahead detection then the offset on the absolute steering angle signal can be changed or the angle detection means can be stopped and a fault indicated.

1. The system may further include a yaw sensor adapted to detect that the vehicle is travelling in a straight line. The system may be adapted to measure the output of a first sensing means which comprises an absolute steering angle position sensor. It may then calculate an offset to correct the absolute steering angle signal so that it indicates the straight-ahead condition when the vehicle is travelling in a straight line.
The yaw sensor may be adapted to indicate a straight line travel when the quantity:

$$|\text{indicated yaw}| / \text{indicated vehicle speed}$$

is below a certain threshold for a period greater than a certain time. The threshold and the duration can be chosen for the vehicle to which the system is applied. "|.|" indicates absolute value. The calculation must be protected from the case when the vehicle speed is zero, for example calculation may be disabled at low vehicle speeds. The calculation may perhaps only be used when the rate of change in the vehicle speed is low.

2. The system may be adapted to decide that the vehicle is travelling in a straight line by monitoring the values of handwheel velocity and handwheel torque. An electric power steering system may therefore further include means for monitoring the handwheel velocity and means for monitoring the handwheel torque. The system may then be adapted to determine if the absolute value of the handwheel velocity is below a threshold, the absolute value of handwheel torque is below a threshold and the vehicle speed is above a threshold. In this condition it is highly likely that the steering system will be pointing substantially straight ahead. This condition can be made more discriminating by screening out the cases when the vehicle speed , handwheel torque or handwheel velocity are changing at a high rate.

3. Use a steering angle that is averaged over distance. The system therefore includes means for monitoring the average direction of travel of the vehicle. This is very close to straight ahead when large distances are considered. Therefore accumulating an average of the steering angle over distance will show if the absolute steering angle is well-aligned with the true straight-ahead. A low-pass filter may be provided that is adapted to filter the output of a steering shaft angular position sensor with respect to distance. This can be approximated by a time-based filter but a time-based filter will not work correctly at low vehicle speeds. A better approach is to let the input to the filter be an angle α, the filter output be an average angle A, the filter "time-constant" be k, the distance travelled be x and the vehicle velocity v. Then a first order low-pass filter that operates over distance is:

$$\begin{aligned} A &= \int k(\alpha - A)\,dx \\ &= \int k(\alpha - A)\frac{dx}{dt}\,dt \\ &= \int k(\alpha - A)\,v\,dt \end{aligned}$$

The input angle may be compared with the filter output to generate an error signal. The error is multiplied by the "time-constant" and the vehicle speed and is then integrated (over time). Thus, when the vehicle speed is zero the filter output will not change. When the vehicle speed is high the filter output will adapt quickly. This filter can be incorporated into the absolute steering angle detection scheme by applying the filter to the absolute steering angle output; the output of the filter (after an appropriate settling time) can be used to detect the offset that the absolute steering angle has from zero. The offset may be stored in non-volatile memory and restored into the filter integrator for use on the next journey that the vehicle makes.

[0030] The stored offset should be bounded to prevent an excessive value being used. If the filter output exceeds a pre-determined limit, then it may be desirable to disable the absolute steering angle detection scheme until it has been inspected at a service point.

OTHER EPAS DRIVE SYSTEMS

[0031] There are other suitable cases in which two sensing means, each adapted to produce an output of angular position are geared with respect to one another by a train of gears and one sensor rotates with the handwheel and the other sensor rotates at a higher rate. The system of the first aspect may be modified to suit each case. The other cases to consider are listed below:

Pinion-drive: the first sensing means may be located on the driver side of a pinion shaft of a rack-and-pinion steering gear. The motor may then be adapted to drive the pinion instead of the steering shaft via a reduction gearbox as described hereinafter. Of course, this falls within the meaning of the term "operatively connected" to the steering shaft, as will be apparent to the skilled person.

Rack-drive: the first sensing means may be located on the driver side of a pinion shaft of a rack-and-pinion steering gear. The motor drives the rack directly through some gear-train that converts the motor's rotary motion to a linear motion (typically, this is a recirculating ball-nut that drives a lead-screw machined into the rack). The second sensing means may thus be geared to the rack which is geared to the pinion. The gear ratio between the motor and the pinion will be:

pinion revolutions per mm / motor revolutions per mm

Dual-pinion drive: this is a special case of the rack-drive in which the motor is adapted to drive the rack through a second pinion. The handwheel is connected to the first pinion and the first sensing means is mounted on the input shaft of the first pinion. The motor drives the second pinion via a reduction gearbox. Thus the gear ratio between the motor and the "column" angle sensors is:

motor reduction ratio x *second pinion ratio / first pinion ratio*

Although this is a more complex chain, provided it has a non-integer ratio, the rack position detection method can be employed.

[0032] The electric power assisted steering system of the first aspect of the invention produces an angular position signal for the steering shaft. There are many envisaged uses for this absolute steering angle signal. Protection may be sought for any of these uses. These include:

1. Providing a "powered-centering" function in which the electrical motor is adapted to provide a torque to the steering shaft which returns the steering system to the straight-ahead position. The system may be adapted to produce a torque demand that is added to the normal assistance torque demand to provide "powered-centering" that acts to return the road wheels to the straight ahead position when the driver releases the handwheel. For example when the steering system is rotated to steer the vehicle left, a torque that acts to turn the steering to the right may be added to the normal assistance torque and vice versa when the steering is turned to the right.

2. Enabling "soft" steering end-stops in which the EPAS system is adapted to drive the motor with an assistance torque which is reduced when the steering system is near to the end-stops. This prevents the driver from rotating the steering system quickly onto the end-stop and so "soft" end-stops can reduce the shock loads and the associated noise with hitting the end-stop of the steering. Clearly this can be combined with the powered-centering function. The torque may be added in the same manner as the powered-centering torque.

3. Providing a signal for use by a "Vehicle Dynamic Control" system that aims to control the yaw of a vehicle by braking different wheels. A VDC system computes the yaw that is required by the driver from the absolute steering angle and the vehicle speed; the actual yaw of the vehicle is measured by a yaw sensor and the difference between the measured and demanded values is used to control the distribution of the brake force to correct the yaw error. The absolute steering angle can be used as an input to the VDC controller.

4. Providing a signal for use by a damping control system in which the suspension damper units are "stiffened" when the vehicle is cornering. The absolute steering angle signal can be used to give advanced warning that the driver is entering a corner and the damping rate can be increased before the vehicle starts to roll. Once the vehicle is travelling in a straight course, the damping rate may be reduced to give a soft ride.

5. Providing a signal for use by a steering angle control system. Such a system may use a closed-loop feedback controller to generate an EPAS assistance torque that depends on the difference between a demanded steering angle and the absolute steering angle. The demanded steering angle may arise from some vehicle guidance system, for example, this could be a signal from a camera that determines the course of the road by recognising the lane markings or a signal from some roadside equipment that indicates the direction of the road.

[0033] It is envisaged that in at least one arrangement the invention may be successfully implemented in combination with an alternate scheme for detecting the steering angle. The system will be adapted to base its measurements on the output of one or other of the systems depending upon prevailing conditions such as recovery from battery failure.

[0034] One particular alternative system which it is envisaged could be used alongside the present invention is described in our earlier British application No. GB 9900774.7 filed on the 15th January 1999. The disclosure of the earlier application is fully incorporated herein by reference, and is referred to as the "motor position counter" system whilst for clarity the system described herein relating to the first aspect of the present invention is referred to as "non-integer gear sensor" system.

[0035] The earlier dated application discloses an electrical power steering system in which the output from a motor position sensor, typically comprising a number of Hall effect devices, is combined with an index signal from a sensor connected to the steering shaft or the rack or perhaps a yaw sensor to produce an accurate measurement of steering angle by counting transitions in the output of the Hall effect sensors. The index sensor produces an index signal and the counter is reset when the index is produced to ensure the count does not drift out.

[0036] Thus, in accordance with a further aspect the invention provides an electric power-assisted steering system according to the first aspect of the invention in which the second sensing means is further adapted to produce an output signal indicative of angular position of the rotor which undergoes periodic transitions as the rotor rotates, the processing means being adapted to produce a second angular position signal indicative of the angular position of the steering shaft by counting transitions in the output of the second sensing means, the count being reset whenever the output of the first sensing means corresponds to an index position of the steering shaft, the processing means being adapted to combine both the first and second angular position signals to produce an authoritative angular position signal.

[0037] The invention of this aspect thus combines all of the features of the first aspect (producing a first position signal) with those of the invention described in GB9900774.7 and provides an authoritative output based on the output of one or other of the systems.

[0038] The processing means may combine the first and second angular position signals by normally using the second angular position signal to produce the authoritative output whilst using the first angular position signal to verify the second position signal.

[0039] If the two angular position signals differ the output produced by the first aspect of the invention may be used as the basis of the authoritative output. This may continue to be used until the first sensing means produces an index signal and the count is reset. At this time it is known that the count is correct. This allows the system to produce an authoritative output after a fault when the count would otherwise be incorrect for the entire period of operation until the steering shaft rotates such that an index is produces (i.e. the output of the first sensor on the steering shaft is at the index position).

[0040] In an alternative the first angular position signal may be used to reset the count signal without waiting for the steering shaft to cross the index position. This can be done if the first angular position signal is deemed to be reliable. This situation may arise upon power-up, when the count may have been lost yet the first aspect of the invention produces an immediate reliable output.

[0041] It will, of course, be appreciated that the combination of both systems can provide a more accurate and reliable system whilst also providing valuable cross checking. As the systems share physical sensors hardware is minimised. Of course, one physical sensor may produce more than one output, i.e. an incremental output and a continuous output.

[0042] Both systems can be implemented so that they share physical sensors. In use the output of one system may have advantages over that of the other. The following method has been proposed:-

[0043] On power-up, when the power steering system is first energised, the output determined by the motor position counter system is read. This initialises the authoritative angular position signal used within the control system. The output of the column position sensor, which measures absolute position, is used to incrementally update this signal as it has a higher resolution. The output produced by the non-integer gear sensor system is then used as a cross-check to detect steering wheel turn. If there is a large difference between the two signals, then the non-integer gear sensor system output can be used to reset the motor position counter system output and/or the system can stop using the position signal for the remainder of the journey.

[0044] In another situation, if a battery fault occurs and the motor position counter system output is lost (i.e. is unreliable) the counter signal will be invalid and so cannot be used at power-up. In this case the steering angle is not available until the non-integer gear sensor system can identify the correct steering wheel turn. As soon as the turn is

identified the system can resort to using the motor position counter system by resetting the counter when the steering is in the straight ahead position. The normal operation described in the preceding paragraphs, based on the count system, can then be resumed, the non-integer gearing method being used as a back-up for cross-checking.

[0045] There will now be described, by way of example only, several embodiments of the present invention with reference to the accompanying drawings of which:

Figure 1 is an illustration of an electric power steering system in accordance with the present invention;

Figure 2 is a graph showing a sample output from an absolute angular position sensor with a cycle of one revolution varying with the angular position of its associated shaft;

Figure 3 is a graph showing a sample output from an index angular position sensor with a cycle of one revolution varying with the angular position of its associated shaft;

Figure 4 is a schematic diagram of a three phase brushless permanent magnet motor in which three Hall effect sensors sense motor angular position;

Figure 5 is a graph depicting the output from each of the three sensors shown in Figure 4 over a complete revolution of the motor rotor;

Figure 6 is a graph illustrating a typical output signal which can be constructed from the three signals of Figure 5;

Figure 7 illustrates one example for combining the output of the two sensors of the system of Figure 1 to produce a revolution number signal;

Figure 8 illustrates a refinement to the scheme of Figure 7;

Figure 9 shows a scheme for using a motor index signal with information from a steering shaft sensor to produce an absolute steering angle signal;

Figure 10 shows how the scheme of Figure 9 can be adapted to produce a steering angle signal;

Figure 11 shows representative waveforms produced using the scheme of Figure 9;

Figure 12 illustrates output waveforms produced by a system in which both the steering shaft sensor and motor rotor sensor comprise absolute position sensors;

Figure 13 is a block diagram of a scheme for producing the waveforms shown in Figure 12;

Figure 14 is a block diagram of an alternative processing scheme implemented in an electric power assisted steering system in accordance with the present invention;

Figure 15 is an alternate block diagram for the system of Figure 14;

Figure 16 shows operation over a range of two revolutions unambiguously; and

Figure 17 illustrates a system in which the steering cycle is maintained using an accumulation technique in an alternative embodiment of an electrical power assisted steering system of the present invention;

Figure 18 is a schematic block diagram of a method for accumulating angular position from the absolute angle sensor output;

Figure 19 is a further schematic block diagram showing elements to combine the accumulated angular position signal with the revolution count to generate an absolute steering angle measurement; and

Figure 20 is a table (No.2) illustrating the values produced upon rotation of the motor in one embodiment of the present invention.

[0046] Several different electric power steering systems in accordance with the present invention are described hereinafter. Each system has several common features which are illustrated in Figure 1 of the accompanying drawings.

[0047] The system 1 comprises a steering shaft 2 co-operatively connected at one end to a handwheel 3 and at its other end to a pair of road wheels 4 through a rack and pinion 5. The handwheel 3 is adapted to rotate the steering shaft, in turn to displace the rack and eventually to turn the roadwheels. The amount of movement permissible for the handwheel between end stops (so-called "turns for lock to lock") is determined by the road wheel geometry and suspension design which supports the wheels, but in all cases exceeds one complete revolution, two to four revolutions being typical.

[0048] An electric motor 6 is connected to the steering shaft through a reduction gearbox 7 with a ratio p^1/q whereby for p turns of the motor rotor the steering shaft passes through q turns or revolutions. A control circuit (not shown) provides current to the motor 6 in response to the output of a torque sensor 8 mounted on the steering shaft. The torque sensor 8 measures the torque demanded by the driver and from this the motor current is calculated to provide more or less assistance as demanded.

[0049] In addition to the torque sensor 8, an angular position sensor 9 is provided on the steering shaft 2 and a second angular position sensor 10 is provided on the motor rotor. Each sensor produces an output signal, and these signals are fed to a processing means (not shown) to produce a signal indicative of the position of the steering shaft over its complete range of rotation (i.e. for lock to lock).

[0050] The angular position sensors may be one of several types. To aid the understanding of the invention, several possible alternative types of position sensor will first be described although they are not to be considered exhaustive:

Types of angular position sensor

Absolute angle sensor

[0051] This type of sensor produces a signal that represents the angle of a shaft within, for example, a complete revolution. The signal is available instantly with no storage or initialisation needed. Examples of this type of sensor are a potentiometer, a resolver, a synchro and an optical absolute angle encoder.

[0052] In this description, it is assumed that the angular position sensor output is processed to give a measurement that varies between 0 and 1 revolution in the manner shown in fig. 2 of the accompanying drawings.

Index pulse

[0053] This type of sensor produces a single pulse within each revolution of the shaft. The sensor may be a Hall-effect sensor that detects a change in magnetic field that occurs over a small fraction of a revolution (see fig. 3) or active arc. The accuracy of the sensing systems that employ this type of input rely on the active arc of the sensor being small. The sensor should be designed to ensure that this is the case. Of course, it will be appreciated that an absolute angle sensor such as that shown in fig. 2 can be operated as an index sensor, for example by monitoring the angle when the output exceeds a predetermined threshold value.

Brushless motor angular position sensor

[0054] Some EPAS systems use brushless motors in which a motor sensor is used to control the switching, or commutation, of motor windings. Fig. 4 shows a schematic diagram of a 3-phase brushless permanent motor rotor. In this case 3 magnetic sensors (e.g. Hall-effect) are used to sense which rotor magnet is nearby or the angle of a magnetised disc that is mounted on the rotor shaft.

[0055] The three individual sensor signals can be combined to give a signal that (in the case of a 3-phase motor with 6 rotor poles) repeats every 120° of motor rotation; this is shown in fig. 5. Other numbers of phases and/or rotor poles can be used. The key point to note is that the motor angle that is measured is "absolute" (in that it does not require indexing and counting) but it is not unique within a motor revolution. Therefore the motor angle signal is not an index pulse nor a "continuous" signal but consists of a relatively small number of discrete angle measurements that occur more than once per motor revolution. Fig. 6 shows an example in which the individual motor angle signals are converted into a single combined signal with 6 states ranging from 1/6 to 1 in steps of 1/6. The figure shows the discrete nature and higher frequency of the motor angle signal.

[0056] It will also be appreciated that the torque sensor and position sensor may be combined as a single sensor. Indeed, a single multi-purpose output signal may be produced by the sensor from which a torque value and an angular position value can be extracted.

[0057] All the systems described hereinafter as examples rely on the non-integer ratio of the gearbox to produce a "beat" frequency between the outputs of the two sensors from which a measurement of the angular position of the

steering shaft can be detected over a range greater than can be achieved using a single sensor on its own. They differ principally in the choice of sensors used, and the process used to calculate the angular position.

Method 1 - Absolute angle sensor on motor shaft and index on column shaft

[0058] In this case an angular position sensor on the column measures the angle of the steering column at *one particular point in its revolution* - i.e. an index signal is generated when the column angle lies in a small range of angles. The angular position sensor is ideally situated close to the EPAS gearbox so that the measurement is not affected by any compliance (e.g. in the torque sensor). A second angular position sensor measures the absolute angle of the motor over a full revolution.

[0059] The motor is geared to the column via a reduction gearbox which has a <u>non-integer ratio</u>. That is, the motor turns through p/q revolutions for each revolution of the column where p and q are integers such that :

$$q > 1$$

and

$$p > q \qquad \text{(i.e. motor rotates faster than column)}$$

and

$$gcd(p,\, q) = 1 \qquad \text{("}gcd\text{" = "greatest common divider")}$$

[0060] For example, for a gear ratio of 34:10, we have $p = 17$ and $q = 5$ giving $17/5 = 34/10$ with all of the conditions met. If these conditions are met it is possible to measure the number of revolutions of the column using a system in accordance with the invention. This is achieved by using the non-integer relationship between the two angle measurements.

[0061] For illustrative purposes assume that the column shaft is at an angle where the column sensor detects the index pulse and the motor is rotationally positioned so that the motor angle sensor gives a reading of "zero". If the column is rotated by one full revolution then the column sensor will again detect the index but the motor will rotate through p/q revolutions. The motor angle measurement cannot accumulate all of the motor revolutions but will indicate the fraction of a revolution given by:

$$(p - n\,q)\,/\,q$$

where n is the integer that gives

$$0 \le (p - n\,q)\,/\,q < 1$$

i.e. so that the motor angle measurement is in the range of the sensor output.

[0062] After r revolutions of the column, the motor will have rotated through $(r\,p)\,/\,q$ revolutions and the motor angle sensor output will be:

$$(r\,p - n\,q)\,/\,q$$

where n is a (different) integer chosen so that

$$0 \le (r\,p - n\,q)\,/\,q < 1$$

[0063] When $r = q$, then $n = p$ and the motor angle measurement will be zero. Therefore after q revolutions, the motor and column sensor outputs will assume the same relationship that they started in. For any further revolutions after this the pattern will repeat.

[0064] Thus the motor angle when the column passes through its index point will vary as the column makes complete revolutions. This can be illustrated by an example. Taking $p = 17$ and $q = 5$ the values for each column revolution are given in table 1.

Column revolutions $= r$	-3	-2	-1	0	1	2	3	4	5	6
Number of motor revolutions $= r\,p\,/\,q$	-51/5	-34/5	-17/5	0	17/5	34/5	51/5	68/5	85/5	102/5
Number of complete motor revolutions $= n$	-11	-7	-4	0	3	6	10	13	17	20
Motor position sensor measurement $=(r\,p - n\,q)/q$	4/5	1/5	3/5	0	2/5	4/5	1/5	3/5	0	2/5
Number of $1/q$ $= (r\,p - n\,q)$	2	1	3	0	2	4	1	3	0	2

Table 1 : Example with p = 17 and q = 5

[0065] Table 1 shows that the motor angle measurement can be used to uniquely identify column revolutions from -2 revolutions to +2 revolutions with the pattern repeating after 5 revolutions. Thus the absolute angular position of the steering column can be identified over a number of revolutions and hence the absolute steering angle can be obtained.

[0066] Fig. 7 shows a scheme for using a column index pulse with information from the motor angle sensor to generate a revolution number signal by combining the measurements from a column index sensor and a motor absolute angle sensor. The operation of the blocks is described below:

Sample & hold

Captures the motor angle whenever the column index pulse is present.

Gain

Multiplies sampled motor angle by q.

Round

Rounds the input to the nearest whole number.

Offset look-up

Looks up the number of column revolutions away from centre for the sampled motor angle using a table like table 1. The input to the look-up table is row 5 of table 1 and the output of the look-up table is row 1 of table 1. If the column and motor angles are not synchronised at zero, the look-up table must take this into account or an offset should be added to the motor angle.

[0067] Fig. 8 shows a refinement in which the system of fig. 7 is combined with an accumulate angular position block shown in fig. 18 and a calculate multi-turn signal block shown in fig. 19 to generate the steer angle signal. The motor angle measurement is accumulated and then scaled by the gearbox ratio ($q\,/\,p$) to convert it into units of column revolutions. The revolution number is calculated by the scheme shown in fig. 7 and the outputs of these blocks are fed into the calculate multi-turn signal block.

[0068] The accumulate angular position block may thus be implemented in the manner shown in fig. 18. Two triggers are provided, a first one of which triggers on the trailing edge of the output from the absolute position sensor and second one of which triggers on the rising edge. When the first one triggers, a count up signal is generated which causes the value stored in a revolution counter to be incremented. Likewise, when the second one triggers, a count down signal is generated and the value in the revolution counter is decremented. Thus, the revolution counter value corresponds to the number of complete cycles of the absolute position sensor output from its arbitrary zero position.

[0069] The calculate multi-turn signal block may be implemented as shown in fig. 19. A signal indicating the number of revolutions of the shaft (such as can be derived from the steps set out in fig. 18) is combined with the accumulated angle signal. Since the revolution number is only valid at one particular angle of the shaft, a "valid revolution measure-

ment flag" is provided to indicate when the revolution number signal is valid and trigger a sample and hold block that is used to store any offset needed to correct the accumulated angle value. A latch can be used to generate an "absolute angle valid" flag when the first valid revolution number is received.

[0070] Measures to reduce the sensitivity to noise, manufacturing tolerances, gearbox backlash, compliance or offsets in the sensors have not been described. These are omitted for clarity but any practical implementation would have to be made tolerant of noise and timing issues (such as allowing the looked-up offset to stabilise before sampling it).

[0071] The processing of the output signals can be implemented by using either electronics hardware or a software program running in a microcontroller or by a combination of the two. If the scheme is implemented in software, then the sample rate of the software should be selected to avoid aliasing of the signals and provision must be made to give a rapid response to the column index pulse.

[0072] The absolute steering angle will not be valid until a column index pulse has been generated by the column movement. If an indexed incremental sensor is used the absolute steering angle measurement will not be valid until both the column and the motor sensor have been indexed.

[0073] The resolution of the steering angle measurement will depend on the resolution of the motor sensor : if the sensor can resolve 1 degree on the motor shaft then q/p degrees of column movement can be resolved. The accuracy will depend on the accuracy of the motor angle sensor and the arc-width of the column index pulse: if the column index pulse width is 5 degrees "wide" then the steering angle measurement can determined to within 5 degrees provided the motor sensor is accurate to better than $5p/q$ degrees. The motor angle sensor must have sufficient resolution and accuracy to allow the differences in motor angle at each column revolution to be resolved. That is, the motor angle sensor must be able to resolve q different angles to an accuracy of better than $\pm q/2$.

[0074] Therefore, in this example, a motor angle sensor with a resolution of just 5 different angles could provide a steering angle signal. The disadvantage of using such a coarse resolution is that the column angle would only be resolved to 85 different angles in a revolution.

Method 2 - absolute angle sensor on column shaft and index on motor shaft

[0075] In this case an angular position sensor on the column measures the angle of the steering column within each revolution. A second angular position sensor measures the angle of the motor at one particular point in its revolution - i.e. an index pulse is generated when the motor passes some datum.

[0076] As before, the motor is geared to the column via a reduction gearbox with a <u>non-integer ratio</u> of p / q where p and q are integers such that :

$$q > 1$$

and

$$p > q$$

and

$$gcd(p, q) = 1$$

[0077] Assume that the system is positioned so that when the column is on the straight-ahead revolution the column angle measurement reads "zero" and the motor index pulse is active. In practice it will be difficult to exactly align the column zero position and the motor index pulse and so provision for offsets away from this condition should be made. As the column and motor rotate, the motor sensor will generate an index pulse on every revolution of the motor shaft. When the index pulse occurs, the column angle will be

$$m\,q\,/\,p$$

where m is the number of complete revolutions the motor has made (thus m is an unknown integer). The column angle measurement will be given as

$$c = m\,q\,/p - r$$

where c is the column sensor output in revolutions and r is the number of complete revolutions that the column has made. The column sensor output is constrained to lie between 0 and 1 revolution:

$$0 \le c < 1$$

[0078] Thus the value of c at each motor index pulse is determined by the number of motor revolutions (m) and the number of column revolutions (r) which are both unknown integers. We wish to find the value of r so that the steer angle can be determined. The value of r can be found from the remainder after an integer number of q/p are subtracted from c. Let d be the remainder and s be an integer. Then

$$d = c - s\,q / p$$

where d is constrained to be in the range

$$0 \le d < q / p.$$

Then substituting the equation for c gives:

$$\begin{aligned} d &= c - s\,q / p \\ &= m\,q / p - r - s\,q / p \\ &= (m - s)\,q / p - r \end{aligned}$$

so that integer s will cancel out the unknown integer m as well as part of r to allow d to take on values of 0 to $(q\text{-}1)/q$ in steps of $1/q$. Therefore d can have one of q different unique values. These values will correspond to different values of r. For each particular set of different values of q and p the design must be checked to ensure that there is a one-to-one relationship between the remainder, d, and the revolution number, r, as illustrated by the following example.

[0079] Make $p = 17$ and $q = 5$. Figure 20 is a table which shows the values that arise as the motor rotates.

[0080] The table in Figure 20 shows that the combination of steering shaft angle and motor index pulse can be used to uniquely identify steering shaft revolutions from -2 to +2 revolutions by looking up r against $p \times d$. The identified number of revolutions can be added to the measured steering shaft angle to allow a steering angle position to be determined.

[0081] Fig. 9 shows a scheme for using a motor index pulse with information from the steering shaft angle sensor to generate an absolute steering angle signal. The steering shaft angle sensor is assumed to produce a normalised angle measurement that varies from 0 to 1. The operation of the blocks is described below:

Sample & hold

Captures the steering shaft angle whenever the motor index pulse is present.

Gain

Multiplies the captured steering shaft angle by p.

Rounding block

Rounds the input to the nearest integer to calculate the index to the look-up table.

Revolution look-up

Looks up the steering shaft revolution from a table. For example, the table in Fikgure 2 shows the relationship between the overall steering shaft angle and the angle measured by the steering shaft sensor when the motor index is valid. The look-up table can be constructed from rows 2 and 4 of trhe table in Figure 20. Table 3 shows an example of the look-up table for the example of $p = 17$ and $q = 5$. This is row 4 and row 2 of table 2. The look-up index is an integer that can vary between 0 and p. The look-up table output is the bottom row of table 3 multiplied by q/p (for example, with an input of 3, the output is $4 \times 5/17 = 20/17$). Note that 2 possible outputs are shown for inputs of 11 and 16. These are the values where the output "wraps" around. Either the positive or negative output must be chosen when the system is calibrated. The choice of the value will depend on the offsets that are used between the motor and steering shaft angle sensors. If the negative values are chosen, then the look-up table will output a number between -40/17 and 40/17 revolutions - i.e. ±2.353 revolutions. If the steering shaft moves outside this range the output will "wrap" to an incorrect value.

[0082] If the shaft and motor angles are not synchronised at zero, the table must take this into account or a suitable offset must be added to the steering shaft angle signal.

Row 4 $\times p$	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row 2 $\times p/q$	0	7	-3	4	-6	1	8	-2	5	-5	2	-8 or 9	-1	6	-4	3	-7 or 10	0

Table 3: Example of look-up table for $p = 17$ and $q = 5$

[0083] Fig. 10 shows how the scheme in fig. 9 is combined with the accumulate angular position block and the calculate multi-turn signal block to generate the steer angle signal. The column angle measurement is accumulated. The revolution reference is calculated by the scheme shown in fig. 9 and the outputs of these blocks are fed into the multi-turn block.

[0084] The absolute steering angle will not be valid until a motor index pulse has been generated. If an indexed incremental sensor is used, the absolute steering angle measurement will not be valid until both the column and the motor sensor have been indexed. Some results from this scheme are shown in fig. 11. With the scheme shown the revolution number is updated on every index pulse. The complete scheme could use the repeated updates to check for errors and inconsistencies and to ensure the robustness of the measurement system.

[0085] The resolution of the steering angle measurement will depend on the resolution of the column sensor. The accuracy will depend on the "arc width" of the motor index pulse : if the motor index pulse width is 5 degrees "wide" then the, steering angle measurement can determined to within $5q/p$ degrees. The column sensor must have sufficient resolution and accuracy to allow the differences in angle at each motor revolution to be resolved. Therefore it must be able to resolve p different angles to an accuracy of better than $\pm p/2$.

Method 3 : motor indexing > 1 per rev

[0086] The case described above can be extended to cover a sensor that generates more than one pulse per motor revolution. Assume that a pulse that occurs part-way through a revolution cannot be distinguished from a pulse at the start of the revolution and that k equally-spaced pulses occur per revolution. Then there will be $k\,p\,/\,q$ motor pulses per revolution of the column. For certain values of k, p and q it will be possible to use the same approach as described above by substituting $k \times p$ for p.

Method 4 : continuous column and motor angle sensor measurement

[0087] An alternative system can be constructed which uses 2 sensors that give an output at all angles of the column and motor. These sensors can either measure absolute angle or can incrementally measure angle and count the number of pulses past an index mark. With angular position sensors on both the column and motor, it is not necessary to wait for the steering to be rotated past an index pulse in order to identify the revolution of the column (unless incremental sensors are used, in which case it is necessary to wait for the first index pulse on each sensor) and the revolution can be calculated at more frequent intervals giving better immunity to noise, and out-of-tolerance components.

[0088] The motor is geared to the column via a reduction gearbox with a non-integer ratio of $p\,/\,q$ where p and q are integers as described above.

[0089] Let the actual column angle be:

$$c + r$$

where c is the angle within the revolution (i.e. $0 \le c < 1$) and r is the integer number of complete revolutions away from some reference angle. The column sensor will measure the angle c. The motor rotates with the column via the gearbox. If there is no backlash or compliance in the gearbox the motor angle will be given by:

$$(c + r)\,p\,/\,q$$

The motor sensor will measure the angular position of the motor shaft within the revolution so the sensor output can be expressed as

$$m = (c + r)p / q - w$$

where w is an integer that is a whole number of revolutions so that $0 \leq m < 1$. The 2 measurements of column and motor shaft angles can be processed to give the revolution number. One method to do this is to calculate a "prediction" of the motor angle from the measured column angle assuming that the steering system is on the "zero" revolution (the prediction will only be correct when the column and motor are aligned on the zero steering revolution: the error of the prediction is used to derive the revolution number).
The prediction is calculated using the gearbox ratio:

$$prediction = c\,p / q$$

The difference between the measured motor angle and the predicted motor angle is

$$\begin{aligned} d &= m - prediction \\ &= (c + r)\,p / q - w - c\,p / q \\ &= r\,p / q - w \end{aligned}$$

Recall that r, w, p and q are integers so taking the residue of d will give a number that has values of 0 to $(q\text{-}1)q$ in steps of $1/q$.

[0090] An alternative way of looking at this is to use modular arithmetic. For example, mod-1 arithmetic gives the following results:

x	$x_{\text{(mod 1)}}$
1.0 →	0.0
1.2 →	0.2
3.456→	0.456
-1.2 →	0.2

Number of complete revolutions: r where r is an integer

Actual column angle: $C = c + r$ where $0 < c < 1$

The column sensor will measure the angle: $c = C_{\text{(mod 1)}}$

The motor angle will be: $M = (c + r)\,p / q$

The motor sensor will measure: $m = M_{\text{(mod 1)}}$

The prediction of the motor angle: $prediction = c\,p / q$

The difference is: $d = m - prediction = \{(c + r)\,p / q\}_{\text{(mod 1)}} - cp/q$

The residue of the difference is:

$$\begin{aligned} d_{\text{(mod1)}} &= [\{(c+r)p/q\}_{\text{(mod1)}} - cp/q]_{\text{(mod1)}} \\ &= \{c\,p / q\}_{\text{(mod 1)}} + \{r\,p / q\}_{\text{(mod 1)}} - \{c\,p / q\}_{\text{(mod 1)}} \\ &= \{rp/q\}_{\text{(mod1)}} \\ &= (1/q)\,\{r\,p\}_{\text{(mod } q)} \end{aligned}$$

Thus: $L = q\,d_{\text{(mod 1)}} = \{r\,p\}_{\text{(mod } q)}$

[0091] Therefore the revolution number can be calculated from L. Clearly, due to the (mod q) arithmetic, L can only take on q different values so there are q different recognisable values of r.

[0092] Fig. 12 shows the results from an example using ideal components with no gearbox backlash or compliance. The values of $p = 17$ and $q = 5$ have been used. The top plot shows the measured column angle against the actual column angle. The second plot shows the measured motor angle (solid line) and the "predicted" motor angle obtained by multiplying the measured column angle by p/q. The third plot shows the difference (d) between the 2 signals in the second plot (dashed line) and the (mod 1) residue of the difference multiplied by q (i.e. L); it can be seen that the residue is always an integer multiple of $1/q$. The relationship between L and the number of complete column revolutions is clear. There are q different values which the difference can take. In this case, there are 5 levels so the 2 revolutions either side of the straight ahead position can be uniquely identified. It has been assumed that the motor and column angle measurements are aligned at zero; if this is not the case then offsets should be taken into account.

[0093] Fig. 13 shows a block diagram of a scheme that implements the processing described above. The inputs to this block diagram are a column angle measurement and a motor angle measurement. Both of these quantities are obtained using sensors of the absolute angle type described above. The operation of the blocks is described below:

Gain

Multiplies the column angle by p/q to give the "predicted" motor angle.

Calculate difference

A summing block is used to calculate the difference, d, between the measured motor angle and the predicted motor angle. An offset can be introduced to this sum to compensate for the misalignment of the motor and column sensors.

Modular-1

Calculates the residue of the difference, d, as described above.

Gain

Multiplies the residue of the difference by q to give L.

Round

Rounds L to the nearest integer. This integer is used as an index for the look-up table. In ideal circumstances the fractional part of the difference will be exactly an integer factor of $1/q$. The rounding operation is necessary to compensate for non-ideal effects that can distort the measurements and the calculations. The rounding operation gives a good immunity to small errors. The exact immunity should be calculated for a given set of p and q and then assessed against the performance achievable by the chosen sensors.

Look-up table

Looks-up the revolution number using the index. The contents of the look-up table will depend on the values of p and q. The look-up table can be calculated in this case by considering the values of the inputs and intermediate variables for each column revolution. Table 4 gives an example for $p = 17$ and $q = 5$. The first row of table 4 is the column revolution number. The bottom row of table 4 is the look-up index. It is assumed that the column revolutions of interest are those given in the unshaded areas of table 4. The look-up table must output the top row of table 4 against the index given in the bottom row of table 4.

Column revolutions	$=r$	-3	-2	-1	0	1	2	3	4	5	6
Column sensor output	$=c$	0	0	0	0	0	0	0	0	0	0
Number of motor revolutions	$=(c+r)p/q$	-51/5	-34/5	-17/5	0	17/5	34/5	51/5	[illegible]	[illegible]	102/5
Number of motor revolutions	$=w$	-11	-7	-4	0	3	6	10	13	17	20
Motor angle sensor output	$=m$	4/5	1/5	3/5	0	2/5	4/5	1/5	[illegible]	0	2/5
Prediction	$P=cp/q$	0	0	0	0	0	0	0	0	0	0
Difference	$d=m-P$	4/5	1/5	3/5	0	2/5	4/5	1/5	3/5	0	2/5
Number of 1/q (look-up index)	$=(rp-wq)$	4	1	3	0	2	4	1	3	0	2

Table 4: Example with p = 17 and q = 5

Sum

Adds the revolution number to the column angle measurement to give the steering angle.

[0094] This scheme shows the fundamental elements that are required. Additional components may be included to compensate for offsets, gearbox backlash, initialisation, error detection and any issues associated with the sensors that are used. It is assumed that these components can be designed by someone who is skilled in the art from this teaching.

Method 5 : non-unique motor angle

[0095] The schemes described above can be adapted to work with a brushless motor sensor arrangement. There is an obvious difference in that the frequency of the signal is higher and does not represent a unique motor angle within a complete mechanical revolution of the motor shaft. This difference can be accommodated by considering the ratio between the motor sensor and the column sensor rather than the ratio between the motor and the column. Thus, if the sensor signal repeats n times per column revolution, then the ratio between the motor sensor and the column is:

$$n\,p\,/\,q$$

where p and q are as before. To be able to measure the column revolution, we must ensure that:

$$n\,p > q$$

and

$$gcd(n\,p,\ q) = 1$$

[0096] If these conditions are satisfied then the non-unique nature of the motor sensor can be tolerated. The calculations that are used must be modified to incorporate the factor of "n". Using modular arithmetic, we have:

Actual column angle: $C = c + r$
where $0 < c < 1$ and r is an integer
The column sensor will measure the angle: $c = C_{\text{(mod 1)}}$
The motor angle will be: $M = (c + r)\ n\,p\,/\,q$
The motor sensor will measure: $m = M_{\text{(mod 1)}}$
The prediction of the motor angle: prediction = $c\,n\,p\,/\,q = (n\,p\,/\,q)\ C_{\text{(mod 1)}}$
The difference is: $d = m - prediction = \{(c + r)\ n\,p/q\}_{\text{(mod 1)}} - c\,n\,p/q$
The residue of the difference is:

$$d_{(mod1)} = [\{(c+r)np/q\}_{(mod1)} - cnp/q]_{(mod1)}$$
$$= \{c\,n\,p\,/\,q\}_{(mod\ 1)} + \{r\,n\,p\,/\,q\}_{(mod\ 1)} - \{c\,n\,p\,/\,q\}_{(mod\ 1)}$$
$$= \{rnp/q\}_{(mod1)}$$
$$= (1/q)\,\{r\,n\,p\}_{(mod\ q)}$$

Thus: $L = q\,d_{(mod\ 1)} = \{r\,n\,p\}_{(mod\ q)}$

[0097] Therefore the revolution number can be calculated from L as with the complete motor revolution sensor.

[0098] A further complication is that the brushless motor sensor has a very coarse resolution with large quantisation errors. In the example given above the sensor can resolve 6 different angles within a cycle that repeats 3 times per motor revolution. Thus, in this case, n is 3. The coarse resolution can be dealt with in a number of ways. The essence is to recognise that the motor angle sensor measurement is only accurate at points that are close to the transition from one sensor state to another. This can be achieved by:

a. Running the calculations at the time of a transition in the motor angle sensor state by explicitly recognising the transition. The transition between 2 motor angle states gives a higher resolution angle measurement than the sensor state itself.

b. Using knowledge of the motor velocity and the time since the last motor angle sensor transition to improve the motor angle measurement.

c. Using a filter to exclude the motor angle sensor results that are poorly correlated with the column angle sensor measurements.

d. Some combination of the methods given above.

[0099] A system adapted to work with these sensors is shown in fig. 14 and fig. 15. This uses a simple filter that will only accept motor angle sensor measurements that are well correlated with the column angle measurements. The difference between L and round(L) is used as an "error" signal. When the difference is small, the motor angle sensor output is close to an "ideal" sensor measurement and the resulting revolution result is used. When the difference is large, the calculated revolution is discarded. The following analysis is intended to explain this.

[0100] Assume an error, e, is present in the motor angle measurement. For the case of the brushless motor sensor, this error will be a quantisation error. Then the analysis above is modified as below:

The motor sensor will measure: $m = (M + e)_{(mod\ 1)}$

The sensor to prediction difference is: $d = m - prediction = \{(c + r)\ n\,p\,/\,q + e\}_{(mod\ 1)} - c\,n\,p\,/\,q$

The residue of the difference is:

$$d_{(mod\ 1)} = [\{(c + r)\ n\,p\,/\,q + e\}_{(mod\ 1)} - c\,n\,p\,/\,q]_{(mod\ 1)}$$
$$= \{c\,n\,p\,/\,q\}_{(mod\ 1)} + \{r\,n\,p\,/\,q\}_{(mod\ 1)} - \{c\,n\,p\,/\,q\}_{(mod\ 1)} + e_{(mod\ 1)}$$
$$= \{r\,n\,p\,/\,q\}_{(mod\ 1)} + e_{(mod\ 1)}$$

Thus: $L = q\,d_{(mod\ 1)} = q\,\{r\,n\,p\,/\,q + e\}_{(mod\ 1)}$

[0101] The revolution number is calculated from a look-up table that uses L as an index. The integer value of L is obtained by using a round(.) function. When an error, e, is present the value of round(L) will be:

round(L)=	$q\,\{r\,n\,p\,/\,q\}$	for $-0.5 < e \leq 0.5$
	$q\,\{r\,n\,p\,/\,q + 1\}$	for $0.5 < e \leq 1.5$
	$q\,\{r\,n\,p\,/\,q + 2\}$	for $1.5 < e \leq 2.5$
	etc.	

Let $\beta = L - \mathrm{round}(L)$.

Only assume that a revolution estimate is valid when $|\beta| < t$ (where t is a positive threshold, $t < 0.5$). Then value of

round(L) becomes:

round(L) = $q\{r\,n\,p\,/\,q\}$ for $-t<e\leq t$
not valid for $t<e\leq(1-t)$
$q\{rnp/q+1\}$ for $(1-t)<e\leq(1+t)$
not valid for $(1+t) < e \leq (2-t)$
$q\{r\,n\,p\,/\,q+2\}$ for $(2-t) < e \leq (2+t)$

etc.

[0102] Thus, with t less than 0.5, this filter increases the size of error that is required to allow an erroneous revolution number to be generated from $|e| > 0.5$ to $|e| > (1 - t)$. The disadvantage is that the number of valid revolution estimates is reduced.

[0103] Fig. 14 shows how the revolution number is calculated from the motor and column angle measurements. The system is similar to "method 4" but incorporates the filter described above and the factor for the brushless motor angle sensor. The main blocks are:

Gain

Multiplies the column angle by $n\,p\,/\,q$ to give the "predicted" motor angle. Note that this prediction includes the number of repeats per motor shaft revolution, n.

Calculate difference

A summing block is used to calculate the difference, d, between the measured motor angle and the predicted motor angle. An offset can be introduced to this sum to compensate for the misalignment of the motor and column sensors. Another offset may be required to null out the average quantisation error. In the case shown in fig. 6, the offset for the quantisation error will be 1/12 of a motor sensor cycle.

Modular-1

Calculates the residue of the difference d.

Gain

Multiplies the residue of the difference by q.

Round

Rounds the scaled residue of the difference to the nearest integer. This integer is used as an index for the look-up table.

Look-up table

Looks-up the revolution number using the index. The contents of the look-up table will depend on the values of n, p and q. The look-up table can be calculated in this case by considering the values of the inputs and intermediate variables for each column revolution. Table 5 gives an example for $n = 3$, $p = 17$ and $q = 5$. The first row of table 5 is the column revolution number. The bottom row of table 5 is the look-up index. It is assumed that the column revolutions of interest are those given in the unshaded areas of table 5. The look-up table must output the top row of table 5 against the index given in the bottom row of table 5.

Column revolutions $= r$	-3	-2	-1	0	1	2	3	4	5	6
Column sensor output $= c$	0	0	0	0	0	0	0	0	0	0
No. of motor sensor revolutions $= (c + r)\, n\, p\, /\, q$	30.6	-20.4	-10.2	0	10.2	20.4	30.6	40.8	51	61.2
No. of motor sensor revolutions $= w$	31	-21	-11	0	10	20	30	40	51	61
Motor angle sensor output $= m$	0.[illegible]	0.6	0.8	0	0.2	0.4	0.6	0.8	0	0.2
Prediction $P = c\, n\, p\, /\, q$	0	0	0	0	0	0	0	0	0	0
Difference $d = m - P$	0.[illegible]	0.6	0.8	0	0.2	0.4	0.6	0.8	0.[illegible]	0.2
Difference * q (look-up index) $L = q\, d$	2	3	4	0	1	2	3	2	0	1

Table 5 : Example with p = 17 and q = 5

Sum

Calculate "error" term, β.

Window comparator

Produce a "valid" signal when $|\beta| < t$.

Fig. 15 shows how the revolution calculation block (i.e. fig. 14) is combined with an accumulate angular position block and a calculate multi-turn signal block as previously described, to generate the steering angle signal. The column angle measurement is accumulated and the accumulated column angle and the calculated revolution number are fed into the calculate multi-turn block.

Method 6: restricted detection range

[0104] The systems described above can distinguish a limited number of different revolutions depending on the design of the gearbox and the sensors that are employed. In general, the number of revolutions of the handwheel from lock-to-lock are small - typically between 2 and 4. With some gear ratios it is not possible to get complete coverage of the lock-to-lock range. To take a specific example, with a brushless 3-phase motor angle sensor and a 20.5:1 gearbox ratio, we have:

$n = 3$
$q = 2$
$p = 41$

[0105] This only allows 2 different revolutions to be discriminated.

[0106] A useful signal can still be obtained by setting the offsets in the system so that the identified revolution is "0" in the central region and "1" in the extreme regions. The straight-ahead angle can then be identified as being the angle in which the identified revolution is "0" and the column angle sensor is at the (column) straight-ahead angle (see fig. 16). Such an arrangement allows a range from {-2 revolutions + guard band} to {+2 revolutions - guard band} which is nearly 4 turns lock-to-lock (with 4 complete revolutions from one lock to the other, there are 3 points with a "zero" revolution and the column angle sensor output of 0 therefore the straight-ahead position is no longer unique). The size of the

guard band depends on the tolerance stack-up in the steering system and the exact travel of the steering system from lock to lock.

[0107] Once the straight-ahead angle has been identified, the overall steering angle is maintained using the "accumulate angular position" technique described above. Fig. 17 shows a scheme for achieving this that uses elements that have been described above. Essentially, the steering angle is only set when the handwheel passes through the straight-ahead condition.

Claims

1. An electric power assisted steering system (1) comprising: a steering shaft (2) operatively connected at a first end to a handwheel (3) and at its other end operatively connected to at least one roadwheel (4), an electric motor (6) having a rotor operatively connected to the steering shaft (2) through a gearbox (7) having a non-integer reduction gear ratio, a first sensing means (9) adapted to produce an output dependent on the angular position of the steering shaft (2); a second sensing means (8,10) adapted to produce an output dependent on the angular position of the rotor, and processing means adapted to process both output signals to produce an angular position signal indicative of the angular position of the steering shaft (2) over a range of greater than one complete revolution.

2. An electric power assisted steering system according to claim 1 in which both sensors (8,9,10) are adapted to produce a cyclic output signal dependent upon angular position which repeats after a complete revolution or fraction of a revolution.

3. An electric power assisted steering system according to claim 1 or claim 2 in which at least one of the sensors (8,9,10) comprises an absolute angular position sensor which produces a signal indicative of the absolute angular position of the steering shaft (2) or motor rotor within a complete revolution (or part of a revolution)

4. An electric power assisted steering system according to claim 1, 2 or 3 in which at least one of the sensors (8,9,10) comprises an index sensor which is adapted to produce an output signal indicative of the position of the shaft or the motor rotor within a small fraction of a revolution.

5. An electric power assisted steering system according to any preceding claim in which the sensors (8,9,10) are driven directly from the steering shaft (2) or motor rotor without intermediate gearing.

6. An electric power assisted steering system according to any preceding claim in which the gear ratio can be expressed as p/q whereby the motor turns through p/q revolutions for each revolution of the steering shaft, p is greater than q, q is greater than unity, and the greatest common integer factor of p and q is also unity.

7. An electric power assisted steering system according to any preceding claim in which the first sensing means (9) comprises an absolute handwheel position sensor and the second sensing means (8,10) comprises an index sensor adapted to produce an index signal at a known angular position of the motor rotor, said processing means being adapted to sample the output of the first sensing means (9) corresponding to the position when the second sensing means (8,10) produces an index signal, multiply the sampled value by p, round the multiplied value to the nearest integer to produce a reference value and use the reference value to access the corresponding entry in a look-up table, said entry being indicative of the number of revolutions of the steering shaft from an arbitrary zero position.

8. An electric power assisted steering system according to any one of claims 1 to 6 in which the first sensing means comprises an index sensor adapted to produce an index signal at a known angular position of the handwheel with the second sensing means comprising an absolute position sensor.

9. An electric power assisted steering system according to any one of claims 1 to 6 in which both sensing means comprise absolute position sensors.

10. An electric power assisted steering system according to claim 9 in which the processing means is adapted to estimate the angular position of the motor rotor from a measurement of the angular position of the steering shaft (2) assuming it is on its "zero" revolution, the estimate is compared with the actual output signal from the second sensing means, and the difference between the estimate and actual values processed to produce a signal indicative of the number of revolutions of the steering shaft relative to an arbitrary zero angular position.

11. An electric power assisted steering system according to any preceding claim in which the second sensing means

(8,10) comprises a number of Hall effect sensors adapted to detect the angular position of one or more magnets on the motor rotor.

12. An electric power assisted steering system according to any one of claims 1 to 10 in which the motor (6) comprises a brushless permanent magnet motor (6) and the motor sensor comprises a number of Hall effect sensors adapted to detect the position of the magnetic poles.

13. An electric power assisted steering system comprising a steering shaft (2) operatively connected to one or more roadwheels (4) and an electric motor (6) adapted to apply an assistance torque to the shaft (2) which incorporates a means adapted to check the relationship between the actual angular position of the steering angle and the expected angular position of the road wheel carriers.

14. An electric power assisted steering system according to claim 13 in which the measured angular position value of the steering shaft is produced in accordance with any one of claims 1 to 12.

15. An electric power assisted steering system according to claim 13 claim 14 which further includes a yaw sensor adapted to detect that the vehicle is travelling in a straight line.

16. An electric power assisted steering system according to any one of claims 13 to 15 which further includes means for monitoring the handwheel velocity and means for monitoring the handwheel torque.

17. An electric power assisted steering system according to claim 13 or claim 14 which further includes means for monitoring the average direction of travel of the vehicle.

18. An electric power assisted steering system according to claim 17 which further includes a low-pass filter that is adapted to filter the output of a steering shaft angular position sensor with respect to distance.

19. An electric power-assisted seering system (1) according to any preceding claim in which the second sensing means (8,10) is further adapted to produce an output signal indicative of angular position of the rotor which undergoes periodic transitions as the rotor rotates, the processing means being adapted to produce a second angular position signal indicative of the angular position of the steering shaft (2) by counting transitions in the output of the second sensing means (8,10), the count being reset whenever the output of the first sensing means (9) corresponds to an index position of the steering shaft (2), the processing means being adapted to combine both the first and second angular position signals to produce an authoritative angular position signal.

20. An electric power assisted steering system according to claim 19 characterised in that the processing means is adapted to combine the first and second angular position signals by normally using the second angular positon signal to produce the authoritative output whilst using the first angular position signal to verify the second position signal.

21. An electric power assisted steering system according to claim 20 in which in the event that the two angular position signals differ the output produced by the first aspect of the invention is used as the basis for the authoritative output until the first sensing means produces an index signal and the count is reset.

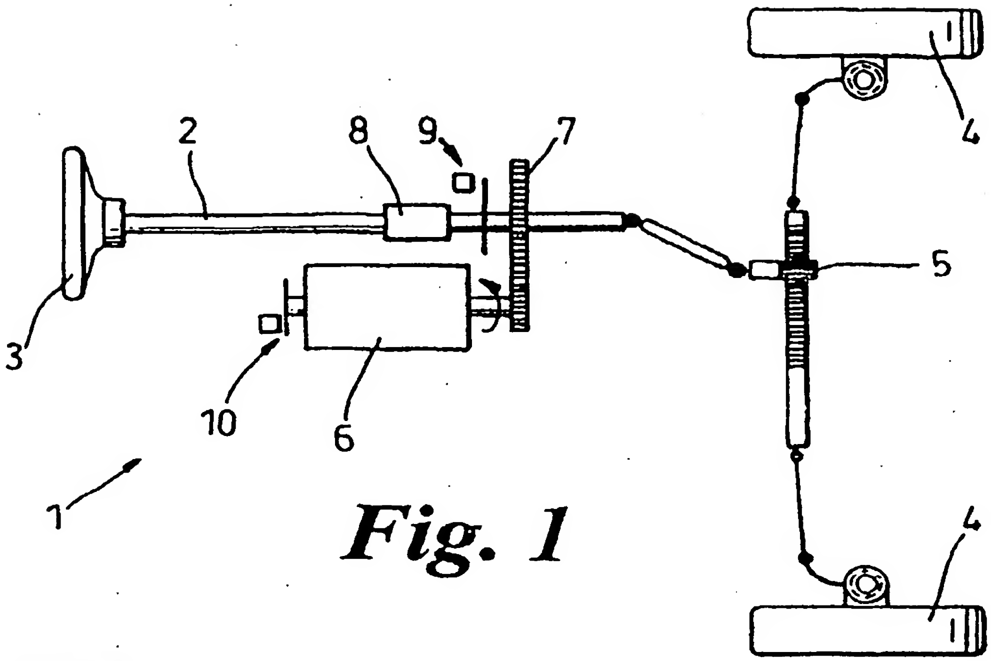


Fig. 1

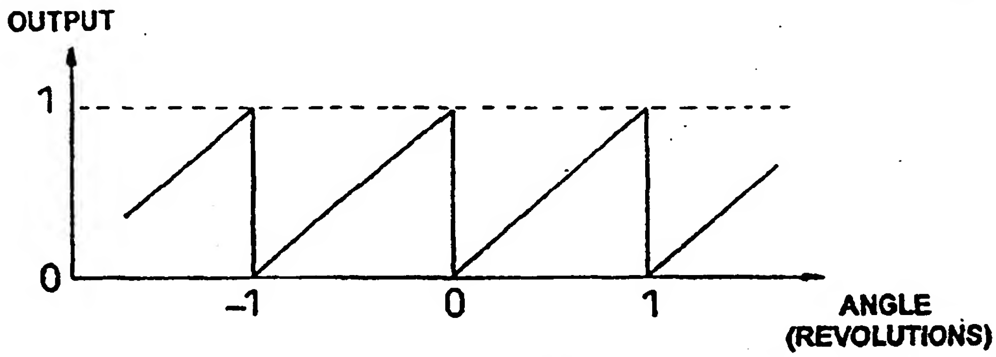


Fig. 2

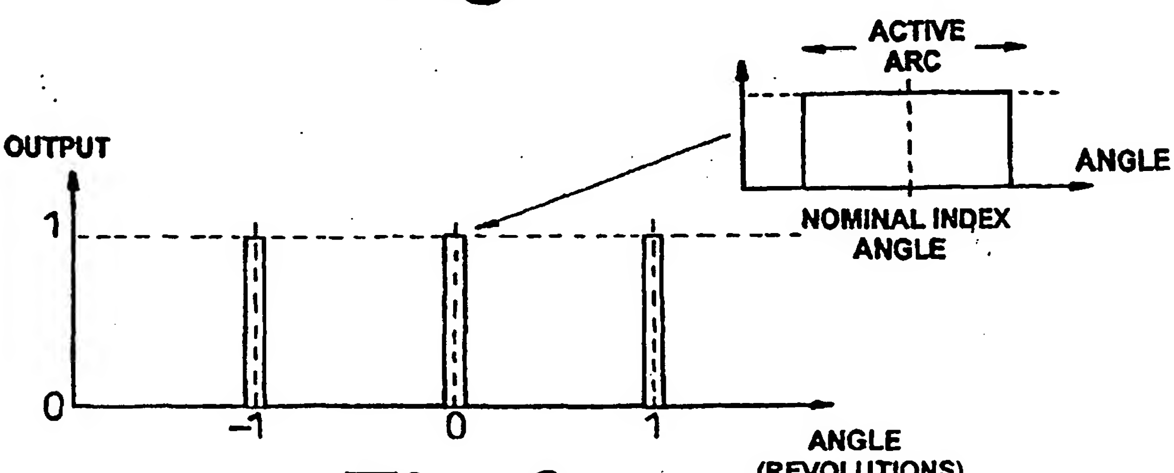
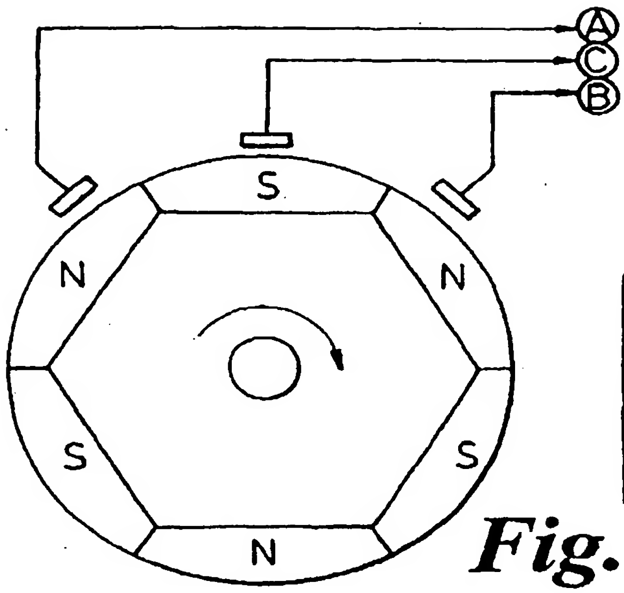


Fig. 3



	A	B	C
1	N	N	S
2	N	S	S
3	N	S	N
4	S	S	N
5	S	N	N
6	S	N	S
1	N	N	S

Fig. 4

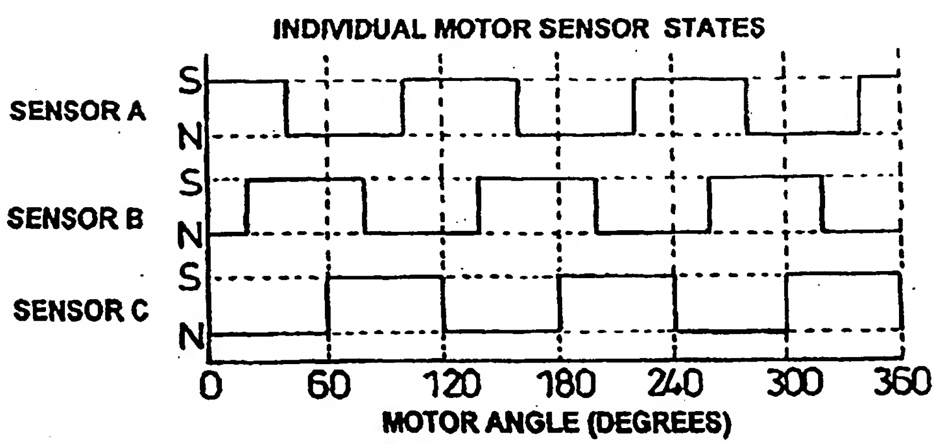


Fig. 5

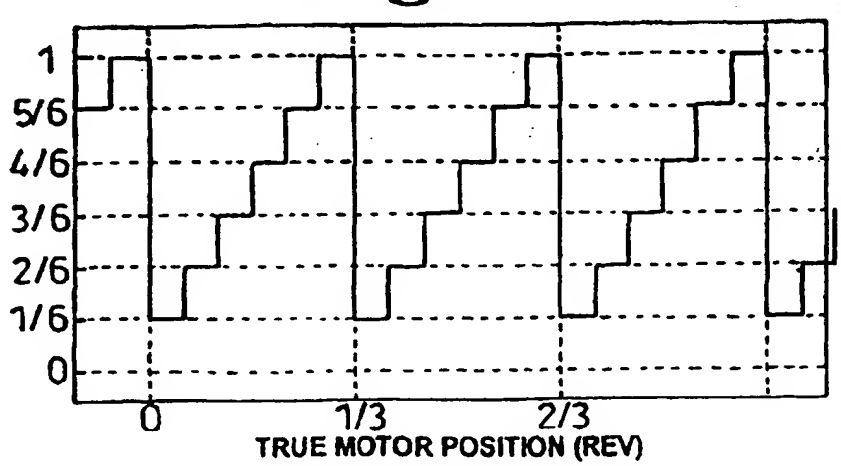


Fig. 6

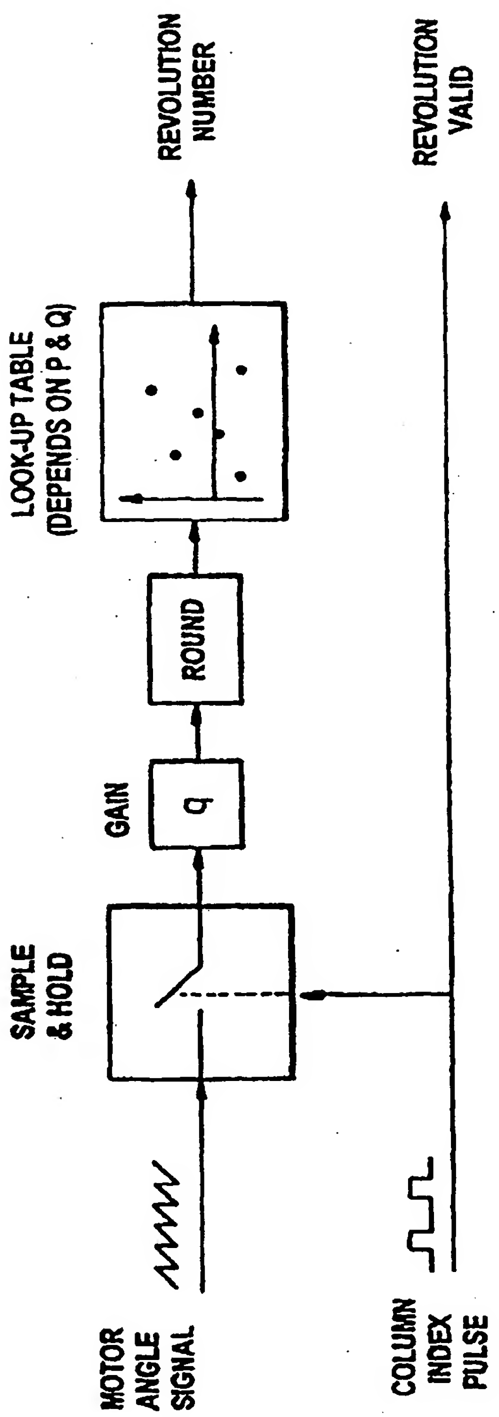

MOTOR ANGLE SIGNAL
SAMPLE & HOLD
GAIN
q
ROUND
LOOK-UP TABLE (DEPENDS ON P & Q)
REVOLUTION NUMBER
COLUMN INDEX PULSE
REVOLUTION VALID

Fig. 7

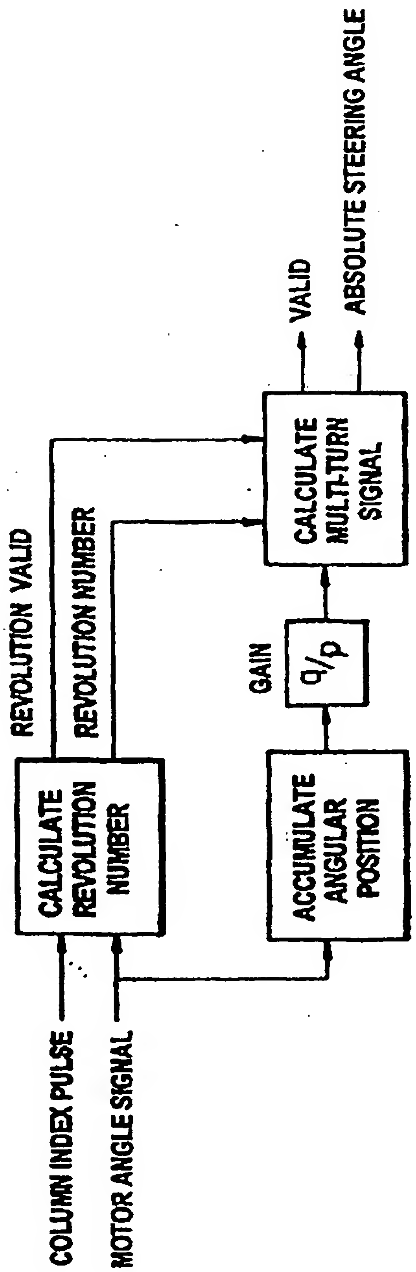

COLUMN INDEX PULSE
MOTOR ANGLE SIGNAL
CALCULATE REVOLUTION NUMBER
ACCUMULATE ANGULAR POSITION
GAIN
q/p
REVOLUTION VALID
REVOLUTION NUMBER
CALCULATE MULTI-TURN SIGNAL
VALID
ABSOLUTE STEERING ANGLE

Fig. 8

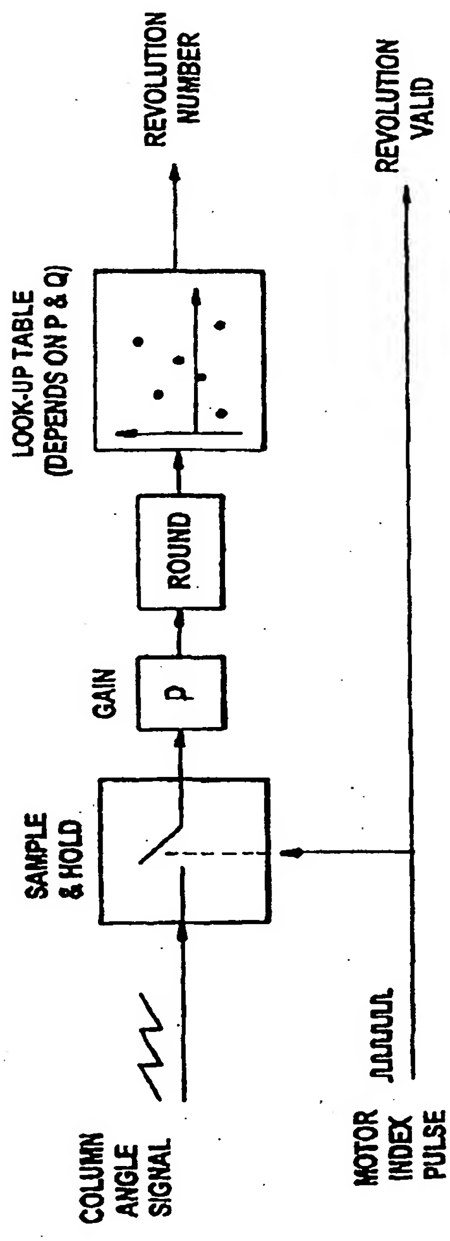

COLUMN ANGLE SIGNAL
MOTOR INDEX PULSE
SAMPLE & HOLD
GAIN
p
ROUND
LOOK-UP TABLE (DEPENDS ON P & Q)
REVOLUTION NUMBER
REVOLUTION VALID

Fig. 9

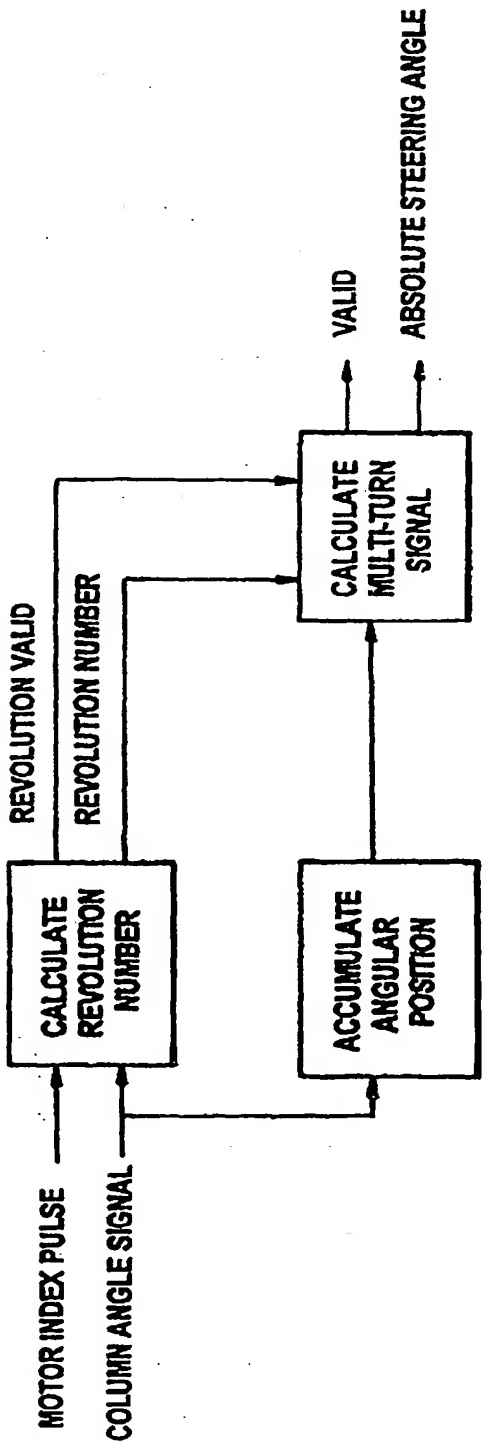

MOTOR INDEX PULSE
COLUMN ANGLE SIGNAL
CALCULATE REVOLUTION NUMBER
ACCUMULATE ANGULAR POSITION
REVOLUTION VALID
REVOLUTION NUMBER
CALCULATE MULTI-TURN SIGNAL
VALID
ABSOLUTE STEERING ANGLE

Fig. 10

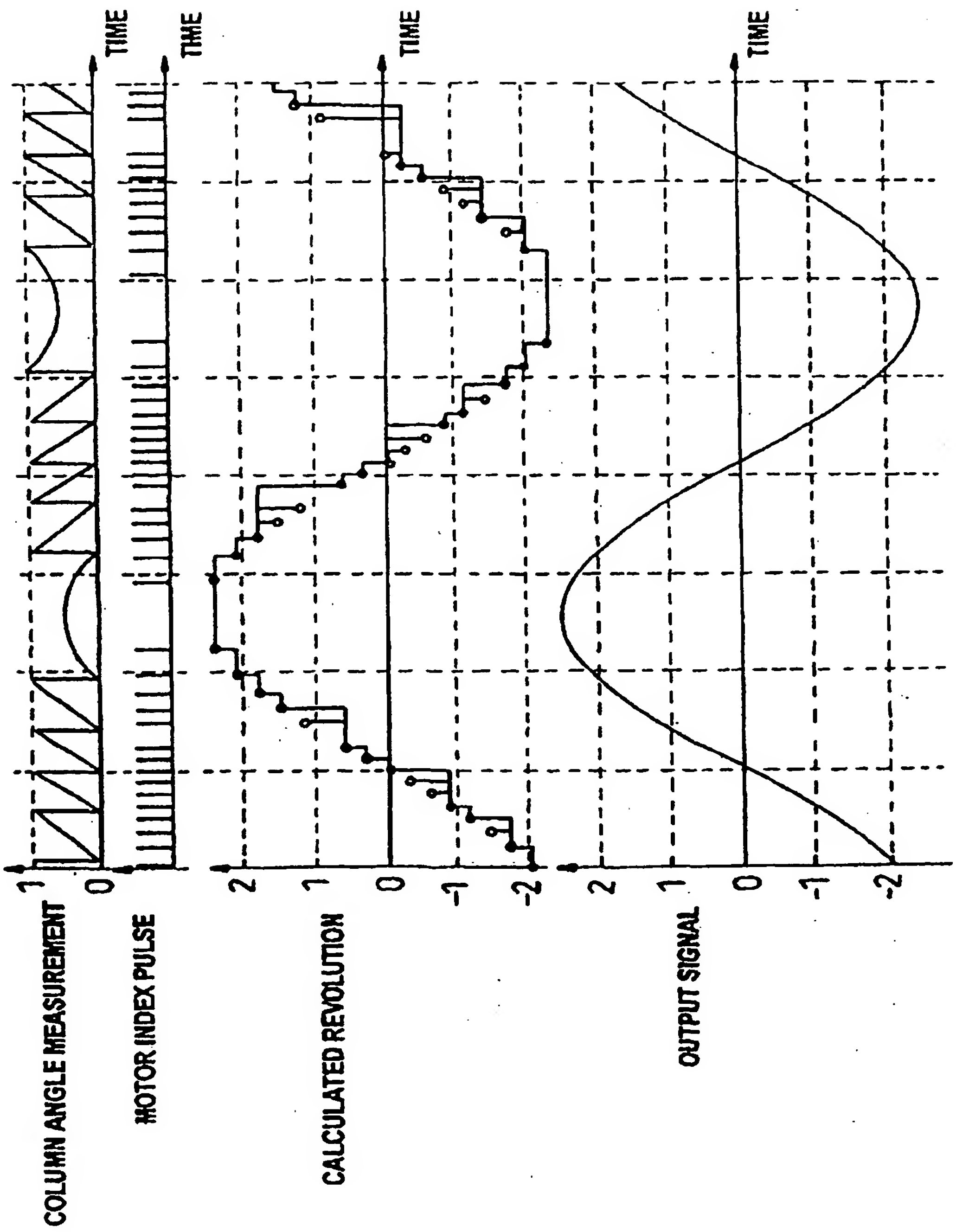

COLUMN ANGLE MEASUREMENT
MOTOR INDEX PULSE
CALCULATED REVOLUTION
OUTPUT SIGNAL
TIME
TIME
TIME
TIME
1
0
2
1
0
-1
-2
2
1
0
-1
-2

Fig. 11

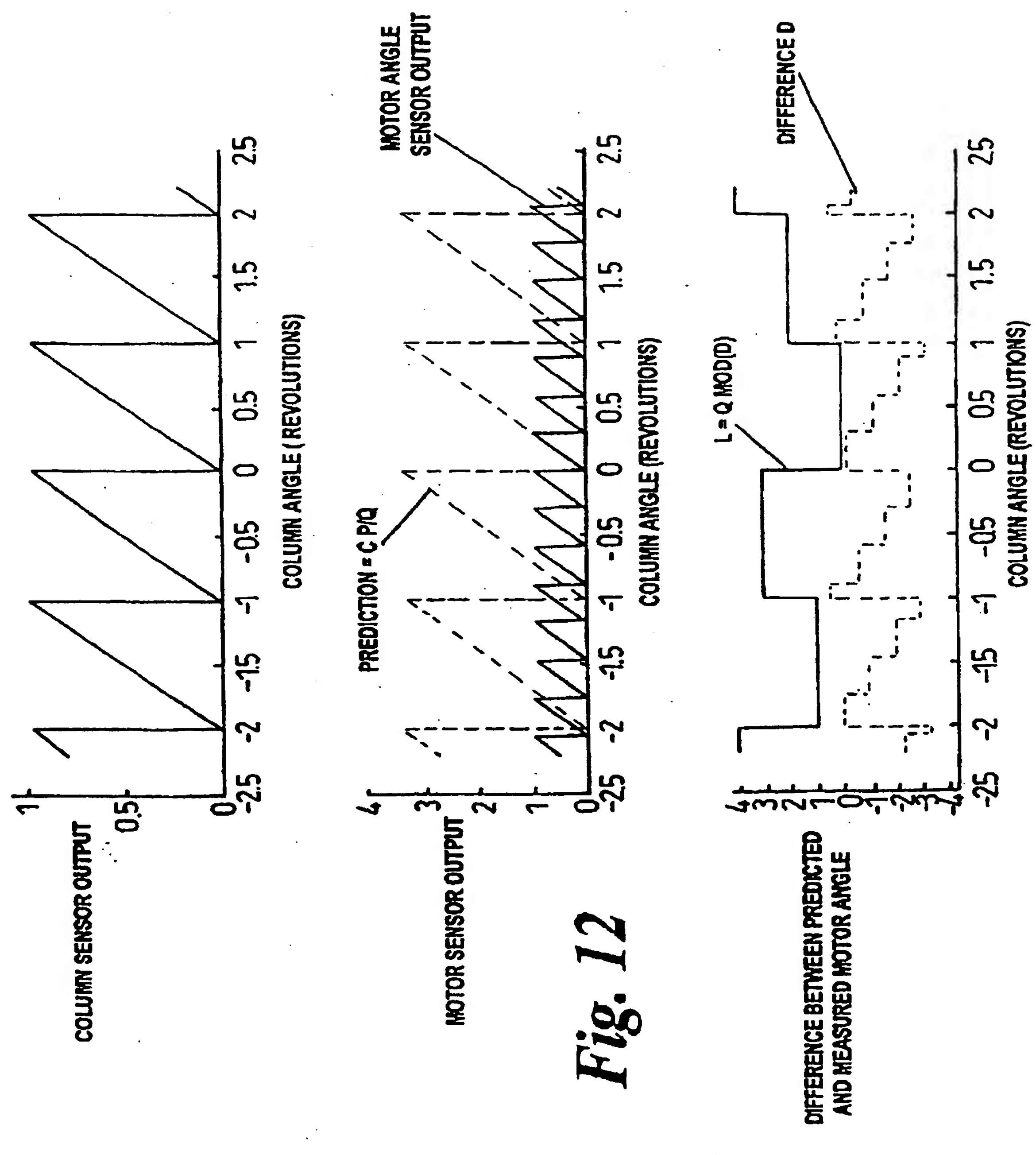

COLUMN SENSOR OUTPUT
COLUMN ANGLE (REVOLUTIONS)
MOTOR SENSOR OUTPUT
PREDICTION = C P/Q
MOTOR ANGLE SENSOR OUTPUT
COLUMN ANGLE (REVOLUTIONS)
DIFFERENCE BETWEEN PREDICTED AND MEASURED MOTOR ANGLE
L = Q MOD(D)
DIFFERENCE D
COLUMN ANGLE (REVOLUTIONS)

Fig. 12

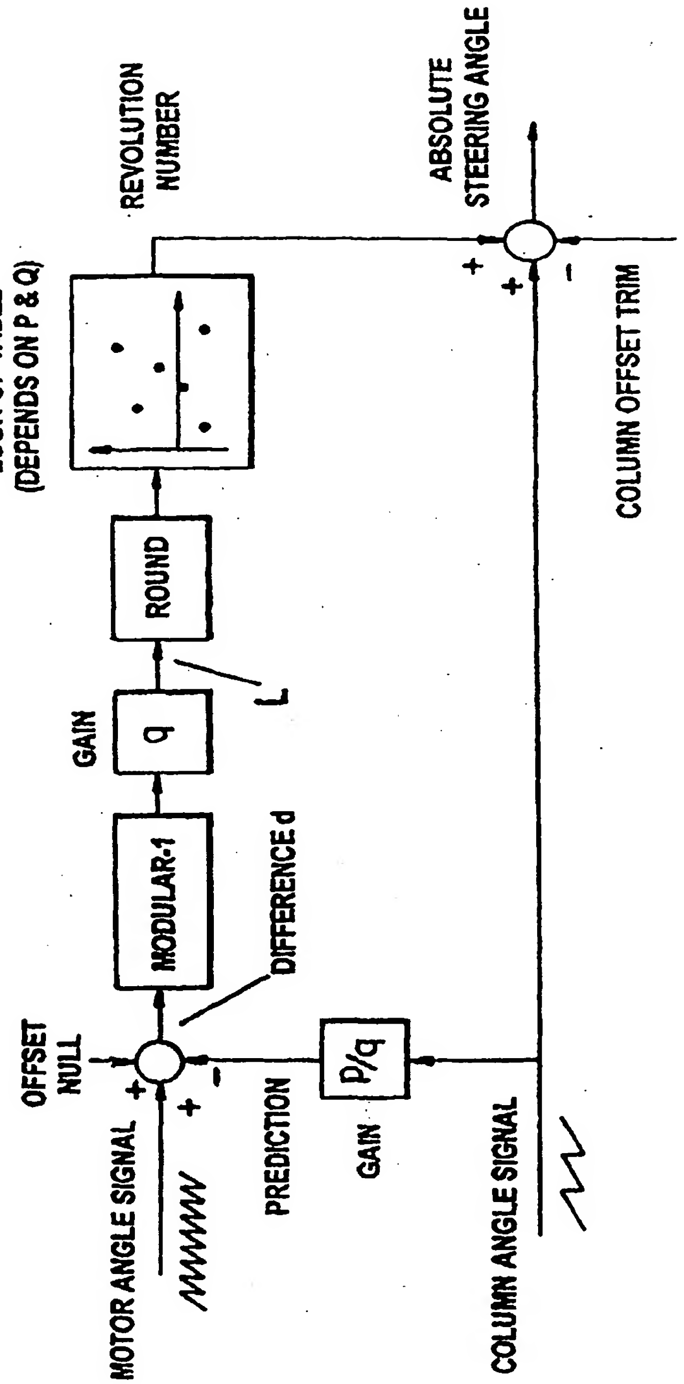
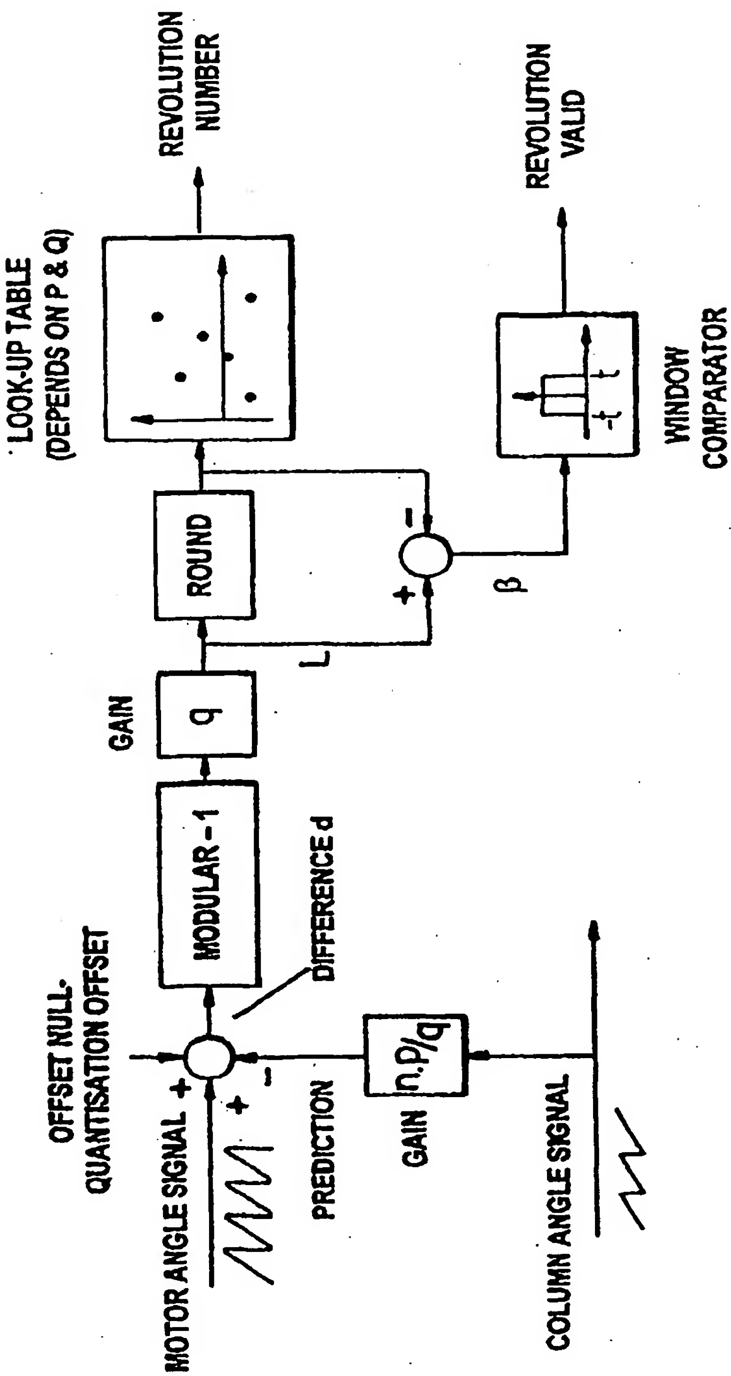

MOTOR ANGLE SIGNAL
OFFSET NULL
+
+
-
DIFFERENCE d
MODULAR-1
GAIN
q
L
ROUND
LOOK-UP TABLE (DEPENDS ON P & Q)
REVOLUTION NUMBER
PREDICTION
P/q
GAIN
COLUMN ANGLE SIGNAL
ABSOLUTE STEERING ANGLE
+
+
-
COLUMN OFFSET TRIM

Fig. 13



OFFSET NULL-
QUANTISATION OFFSET
MOTOR ANGLE SIGNAL
+
+
-
PREDICTION
GAIN
n.P/q
COLUMN ANGLE SIGNAL
MODULAR - 1
DIFFERENCE d
GAIN
q
L
ROUND
+
-
β
LOOK-UP TABLE
(DEPENDS ON P & Q)
REVOLUTION
NUMBER
REVOLUTION
VALID
WINDOW
COMPARATOR

Fig. 14

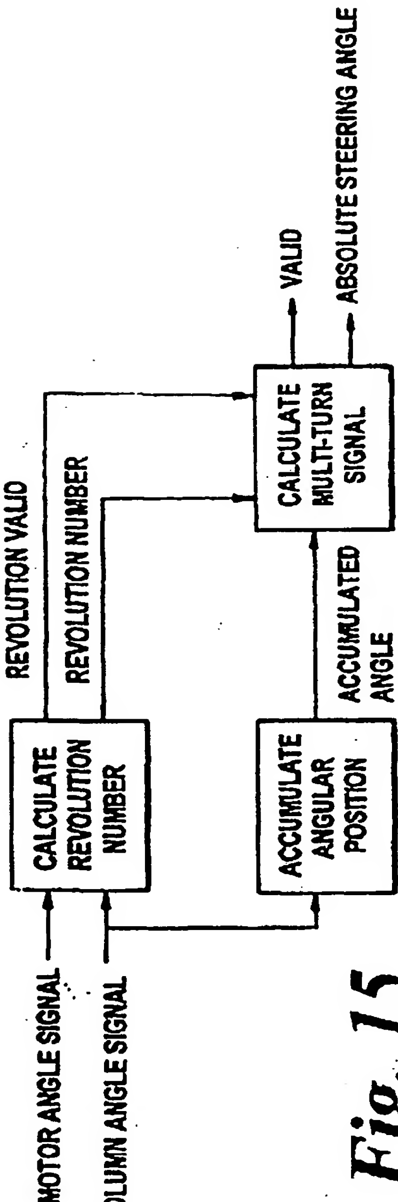

MOTOR ANGLE SIGNAL
COLUMN ANGLE SIGNAL
CALCULATE REVOLUTION NUMBER
ACCUMULATE ANGULAR POSITION
REVOLUTION VALID
REVOLUTION NUMBER
ACCUMULATED ANGLE
CALCULATE MULTI-TURN SIGNAL
VALID
ABSOLUTE STEERING ANGLE

Fig. 15

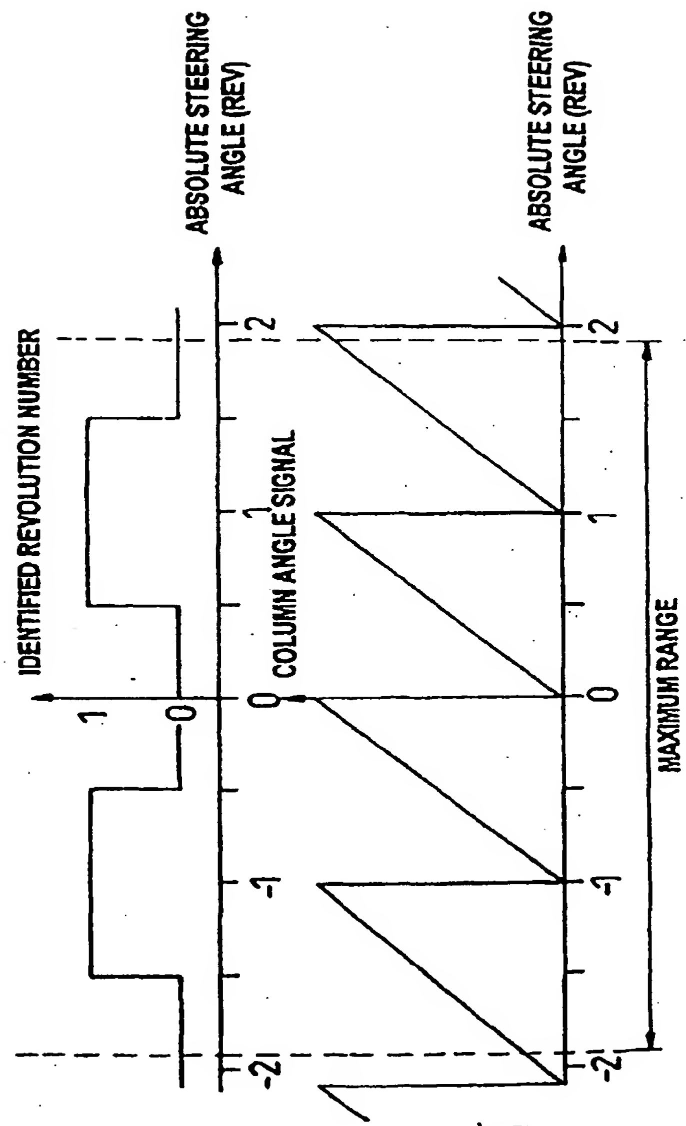

IDENTIFIED REVOLUTION NUMBER
1
0
ABSOLUTE STEERING ANGLE (REV)
-2
-1
0
1
2
COLUMN ANGLE SIGNAL
ABSOLUTE STEERING ANGLE (REV)
-2
-1
0
1
2
MAXIMUM RANGE

Fig. 16

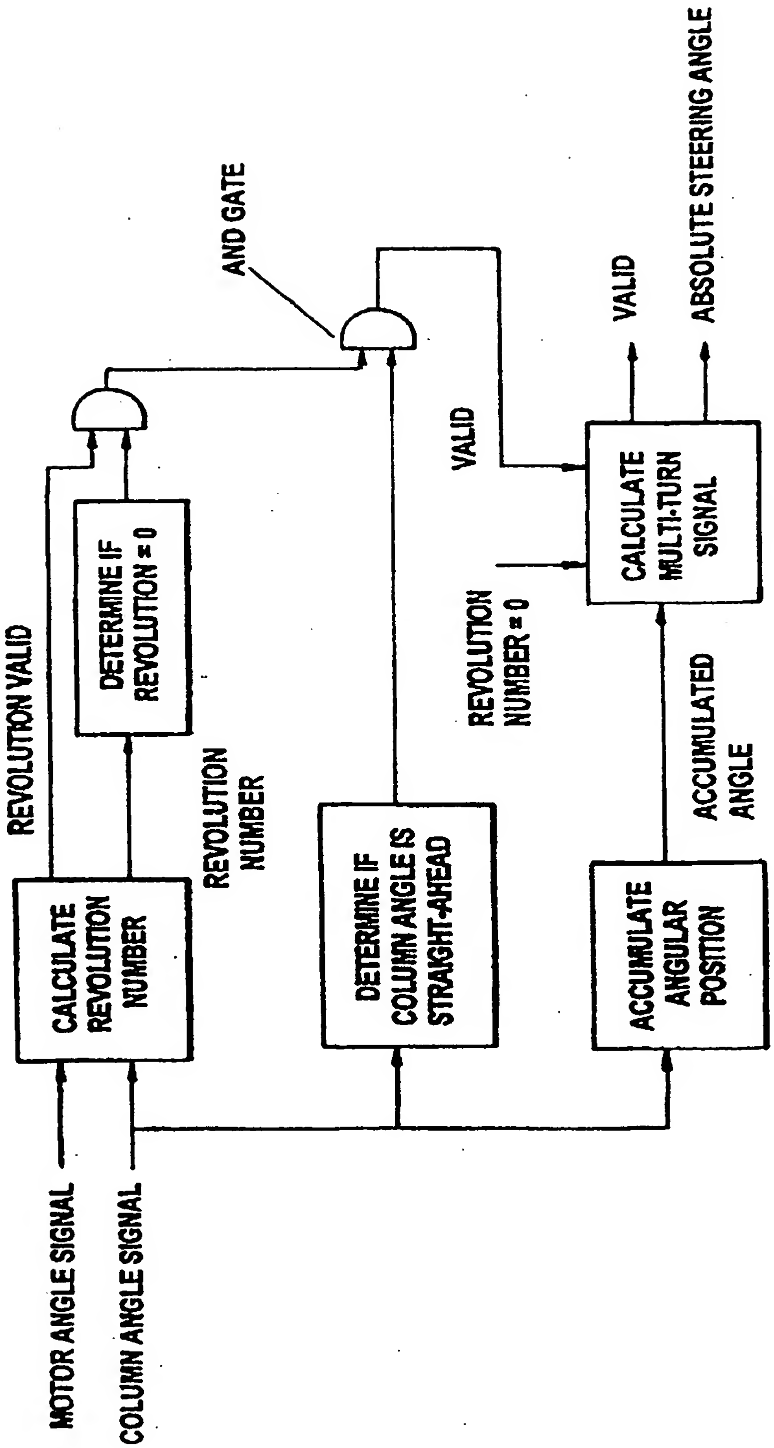

MOTOR ANGLE SIGNAL
COLUMN ANGLE SIGNAL
CALCULATE REVOLUTION NUMBER
REVOLUTION VALID
REVOLUTION NUMBER
DETERMINE IF REVOLUTION = 0
AND GATE
DETERMINE IF COLUMN ANGLE IS STRAIGHT-AHEAD
REVOLUTION NUMBER = 0
VALID
ACCUMULATE ANGULAR POSITION
ACCUMULATED ANGLE
CALCULATE MULTI-TURN SIGNAL
VALID
ABSOLUTE STEERING ANGLE

Fig. 17

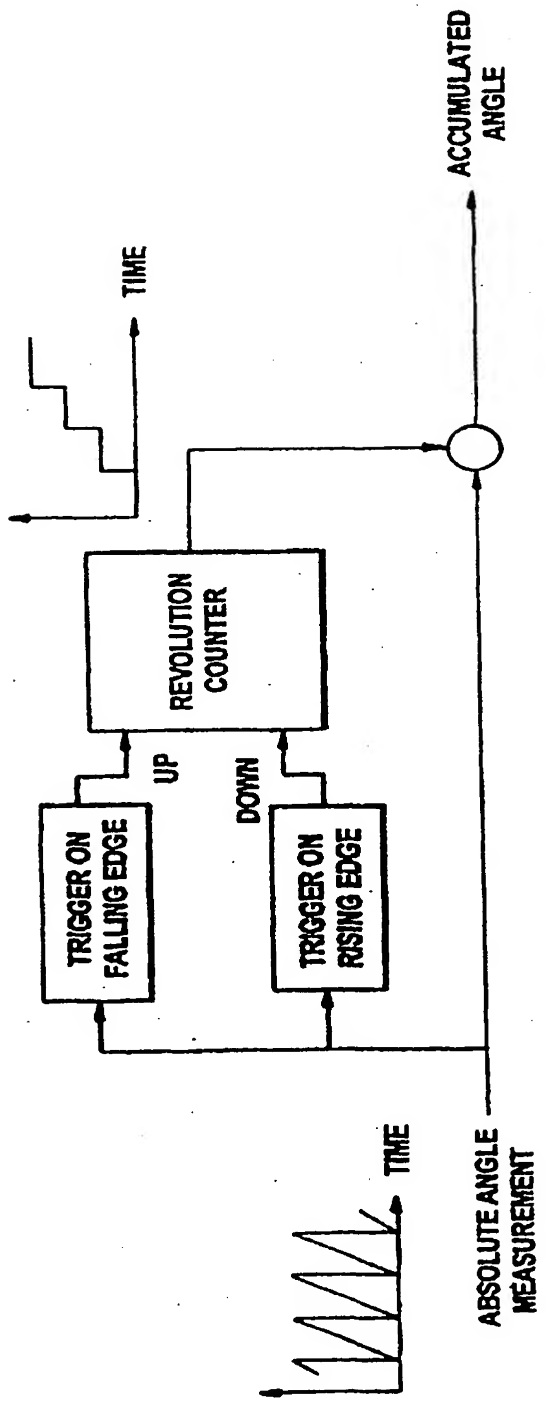

ACCUMULATED ANGLE
TIME
REVOLUTION COUNTER
UP
DOWN
TRIGGER ON FALLING EDGE
TRIGGER ON RISING EDGE
TIME
ABSOLUTE ANGLE MEASUREMENT

Fig. 18

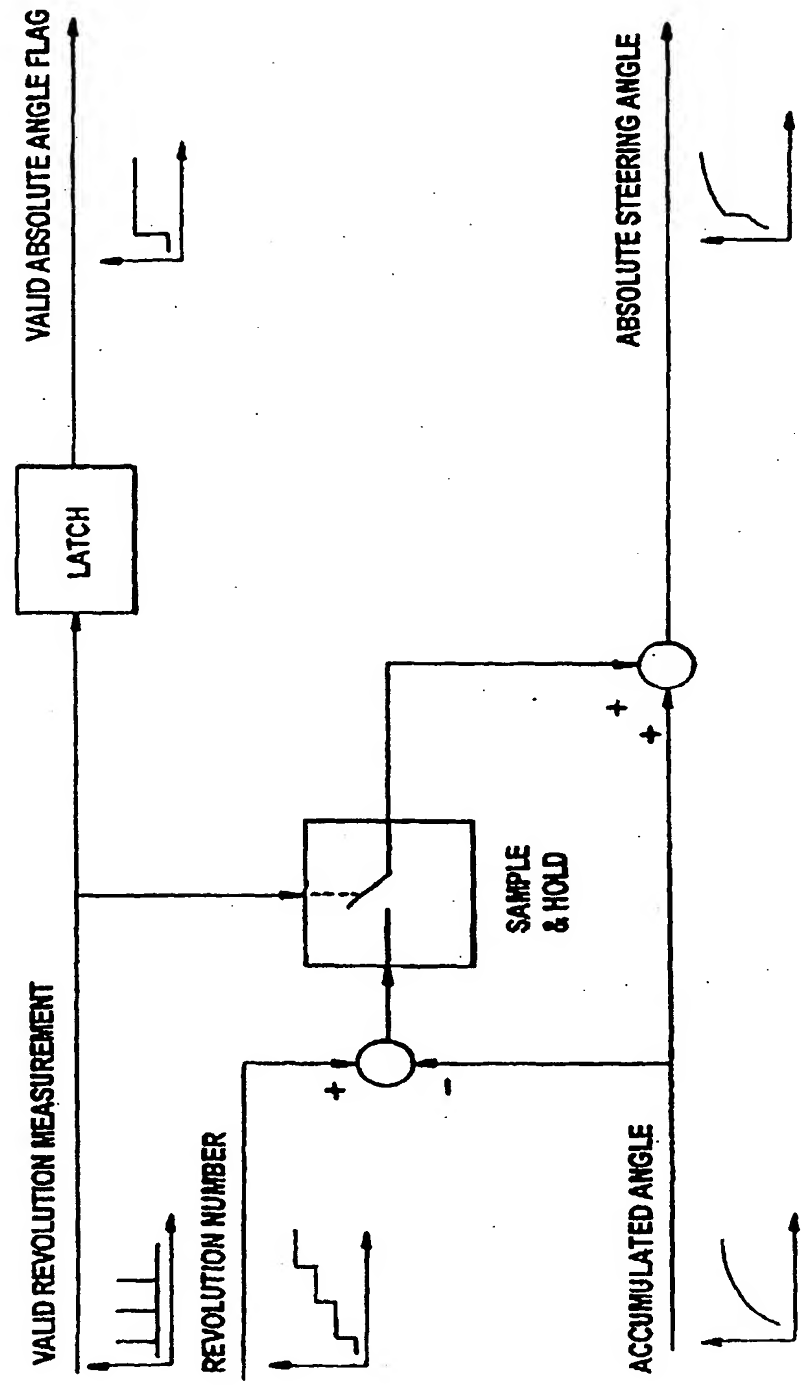

VALID REVOLUTION MEASUREMENT
REVOLUTION NUMBER
ACCUMULATED ANGLE
+
-
SAMPLE & HOLD
+
+
LATCH
VALID ABSOLUTE ANGLE FLAG
ABSOLUTE STEERING ANGLE

Fig. 19

Motor revolutions m	-10	[illegible]	[illegible]	[illegible]	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11
Column angle qm/p	-50/17	[illegible]	[illegible]	[illegible]	-30/17	-25/17	-20/17	-15/17	-10/17	-5/17	0/17	5/17	10/17	15/17	20/17	25/17	30/17	35/17	40/17	45/17	50/17	55/17
Number of column revolutions r	-3	[illegible]	[illegible]	[illegible]	-2	-2	-2	-1	-1	-1	0	0	0	0	1	1	1	2	2	2	2	3
Column sensor output at each motor revolution $c = (qm-pr)/p$	1/17	[illegible]	[illegible]	[illegible]	4/17	9/17	14/17	2/17	7/17	12/17	0/17	5/17	10/17	15/17	3/17	8/17	13/17	1/17	6/17	11/17	16/17	4/17
Number of complete q/p s	0	[illegible]	[illegible]	[illegible]	0	1	2	0	1	2	0	1	2	3	0	1	2	0	1	2	3	0
Fractional part to be subtracted sq/p	0/17	[illegible]	[illegible]	[illegible]	0/17	5/17	10/17	0/17	5/17	10/17	0/17	5/17	10/17	15/17	0/17	5/17	10/17	0/17	5/17	10/17	15/17	0/17
Remainder $d=c-sq/p$	1/17	[illegible]	[illegible]	[illegible]	4/17	4/17	4/17	2/17	2/17	2/17	0/17	0/17	0/17	0/17	3/17	3/17	3/17	1/17	1/17	1/17	1/17	4/17
Remainder multiplied by p pd	1	[illegible]	[illegible]	[illegible]	4	4	4	2	2	2	0	0	0	0	3	3	3	1	1	1	1	4

Fig 20

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 026 068 A3

(12) # EUROPEAN PATENT APPLICATION

(88) Date of publication A3:
17.04.2002 Bulletin 2002/16

(51) Int Cl.7: **B62D 15/02**

(43) Date of publication A2:
09.08.2000 Bulletin 2000/32

(21) Application number: **00300847.1**

(22) Date of filing: **03.02.2000**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: **05.02.1999 GB 9902438**

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(54) **Improvements relating to electric power assisted steering systems**

(57) An electric power assisted steering system (1) is disclosed which comprises a steering shaft (2) connected at one end to the handwheel (2) and at its other end to at least one roadwheel (4), whilst an electric motor (6) is connected to the steering shaft (2) through a gearbox (7) having a non-integer reduction gear ratio. Two sensors (9;8,10) are also provided with one (9) sensing the angular position of the motor rotor and the other (8,10) sensing the angular position of the steering shaft (2). The presence of the non-integer gear ratio produces a beat frequency between the output of the two sensors (9;8,10) from which an unambiguous measurement of the angular position of the steering shaft (2) over a range of greater than one complete revolution can be made. The sensors (9;8,10) may comprise either absolute position sensors or index-type sensors.

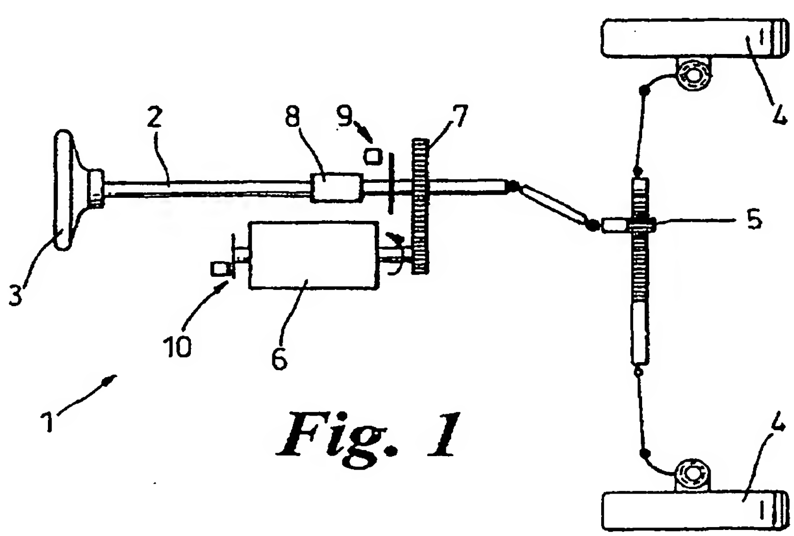

Fig. 1

EP 1 026 068 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 00 30 0847

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X A	DE 195 36 989 A (HONDA MOTOR CO LTD) 11 April 1996 (1996-04-11) * abstract; claims 1-3; figures 1-5,7,8 * * column 2, line 17 - column 2, line 68 * * column 3, line 27 - column 4, line 68 *	13,15,16 14	B62D15/02
A	EP 0 399 405 A (MITSUBISHI ELECTRIC CORP) 28 November 1990 (1990-11-28) * abstract; claim 1; figures 1-3 * * column 2, line 45 - column 4, line 38 * * column 4, line 57 - column 5, line 11 *	1,13,16	
P,X P,A	WO 99 08374 A (BURTON ANTHONY WALTER ;IRONSIDE JOHN MICHAEL (GB); WILLIAMS ANDREW) 18 February 1999 (1999-02-18) * abstract; claims 1-4,7-19; figures 1,5 * * page 1, line 23 - page 3, line 29 * * page 6, line 13 - page 7, line 26 * * page 8, line 22 - page 10, line 12 * * page 15, line 18 - page 16, line 19 *	13 1-9,11, 12,14,16	
			TECHNICAL FIELDS SEARCHED (Int.Cl.7)
			B62D
E,D A	EP 1 020 344 A (TRW LUCAS VARITY ELECTRIC) 19 July 2000 (2000-07-19) * abstract; figures 1-5 * * column 1, line 3 - column 2, line 15 * * column 3, line 12 - column 3, line 32 * * column 3, line 47 - column 3, line 50 * * column 4, line 25 - column 4, line 53 *	1-6,8, 11,12 13-15,19	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	26 February 2002	Balázs, M

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

European Patent Office

Application Number

EP 00 30 0847

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing more than ten claims.

- [ ] Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid, namely claim(s):

- [ ] No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

- [x] All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

- [ ] As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

- [ ] Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

- [ ] None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

European Patent Office

LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 00 30 0847

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. Claims: 1-12, 19-21 (when dependent on claim 1)

   Measurement of absolute steering angle value based on the evaluation of two steering sensors at two locations.

2. Claims: 13-18, 19-21 (when dependent on claim 13)

   Method of applying steering assistance torque incorporating a check to allow for compensation e.g. of wear.

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 00 30 0847

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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26-02-2002

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			JP	8104249	A	23-04-1996
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			EP	1002362	A1	24-05-2000
			WO	9908374	A1	18-02-1999
			JP	2001512960	T	28-08-2001
EP 1020344	A	19-07-2000	BR	0000066	A	17-10-2000
			EP	1020344	A1	19-07-2000
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
H02P 6/16, B62D 5/04, G05B 19/401

A1

(11) International Publication Number: WO 99/08374

(43) International Publication Date: 18 February 1999 (18.02.99)

(21) International Application Number: PCT/GB98/02338

(22) International Filing Date: 4 August 1998 (04.08.98)

(30) Priority Data:
9716658.1 7 August 1997 (07.08.97) GB

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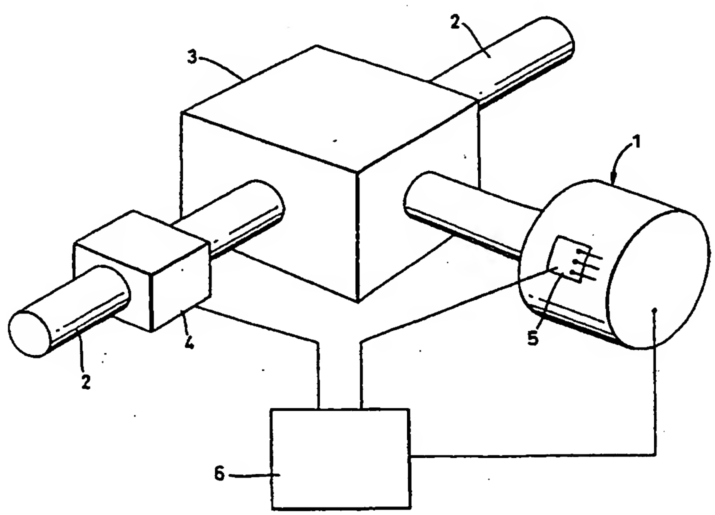
(81) Designated States: BR, JP, KR, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: POSITION SENSING IN BRUSHLESS MOTOR SYSTEMS



(57) Abstract

A method of calculating the position of the rotor of a motor (1) in for example an electrical power assisted steering assembly is disclosed. The method comprises the steps of measuring the output shaft (2) (i.e. steering column) position, and scaling the measured value to produce an estimated motor rotor position value. This estimated value will be relative to an arbitrary datum point, and so the method further includes steps of adding an offset value derived from low resolution measurements of rotor position obtained using Hall effect sensors provided on the motor. Offsets for compensating for backlash and (in a second embodiment) compliance can also be included. Thus, the method allows high resolution information from an output shaft sensor (e.g. a torque sensor with a position dependent output) to be combined with the low resolution output from the Hall effect sensors to produce a high resolution rotor position signal. A correction is also made to allow for "staleness" in the Hall effect sensor output when calculating the offsets by monitoring rotor speed.

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POSITION SENSING IN BRUSHLESS MOTOR SYSTEMS

This invention relates to improvements in electric motors, and especially to an improved method of determining the angular or electrical position of a rotor of a motor.

A brushless permanent magnet motor comprises a rotor supporting a plurality of magnetic elements adapted to rotate concentrically within a stator comprising a plurality of coil windings. The motor can be driven by energising one of the coils to attract the rotor magnets whilst energising another of the coils to repel the magnets. To cause the motor to rotate continuously, the currents flowing through the coils must be switched with rotor position. This switching is known as commutation.

To control the commutation of the motor currents, the position of the rotor must be determined, and it is well known to provide magnetic sensors such as Hall effect sensors to detect the passing of the rotor magnets. In one known arrangement, three Hall effect sensors are located around an inner periphery of the stator and produce a 3-bit digital code representative of electrical position of the rotor. Whilst this is adequate for control of commutation which occurs at precise predetermined locations dependent upon motor geometry, the output of the sensors is relatively crude and low in resolution.

In accordance with a first aspect of the invention, a method of calculating the position at a moment in time of a rotor in a motor which is connected to an output shaft through an intermediate means comprises the steps of:

obtaining a measured rotor position first value indicative of the angular position of the rotor at a first instance in time using a first sensing means provided at the motor;

measuring an output shaft position second value indicative of the angular position of the output shaft at a second instance in time using a second sensing means provided on the output shaft; and

combining said first and second values to produce an estimate of the angular position of the rotor at said moment in time.

Thus, in accordance with the invention, an improved measurement of rotor position can be obtained by employing information from a sensing means provided on the output shaft.

In many systems, a suitable sensing means may already be provided on the output shaft, and so employing information from this sensing means allows an improved method of calculating high resolution position information without the expense and bulk of adding additional high resolution sensors at the motor.

The first sensing means may comprise a plurality of magnetic Hall effect sensors adapted to produce an output signal indicative of the angular position of the rotor. The measurement of motor electrical position used by the method may thus be provided by sampling this output signal. Preferably, the method may comprise the further step of storing the output value from the Hall effect sensors and updating the stored value whenever the output from the Hall effect sensors changes.

In one proposed embodiment, the method may be adapted for use with a motor in an electric power assisted steering system which provides a steering assistance torque to an output shaft. A separate or combined torque and/or a position sensor are typically provided on the output shaft in this system in order to evaluate the degree of assistance to be provided by the motor, and this torque and position sensor can be used to provide the measurement of the angular position of the output shaft, i.e. used as the second sensing means in the method of the invention.

It may be desirable to provide a gearbox between the motor rotor and the output shaft, and a clutch to allow disengagement of the motor from the output shaft. Thus, the intermediate means may comprise at least a gearbox and/or a clutch.

Where the intermediate means comprises a gearbox, the method may comprise the further step of multiplying the measured output shaft position value from the second sensing means on the output shaft by the gearbox ratio to produce a scaled output shaft position value. For example if the ratio of the gearbox is such that the motor rotates one turn for two turns of the output shaft, the output from the position sensor on the output shaft should be halved to produce the scaled output shaft position value.

The scaled value may also be multiplied by one half the number of rotor poles. Thus, the output of the position sensor can be scaled to correspond with the motor electrical position instead of mechanical position.

This is advantageous in that it enables the output shaft position value to be mapped onto the rotor position.

The method may comprise the further step of calculating an offset value indicative of any angular offset present between the rotor position given by the scaled output shaft position value and the actual rotor position.

The method may further comprise the steps of updating the offset value in response to the output of the rotor position sensor. For example, if the measured rotor position value is obtained using (a) Hall effect sensor(s) at the motor (which may also control(s) commutation timing), a high accuracy measurement of rotor position is available at the instant of change of state of the Hall sensor output which can be combined with the scaled output shaft position value to update the value of the offset.

The value of the offset may be updated instantaneously upon a change in state of the Hall effect sensors. This may correspond to a commutation event occurring in a simple control method. Alternatively, it may be updated at some later time when the next reading from the output shaft sensor is obtained, i.e. at the next update of the scaled output shaft position value. In this case, the measured rotor position can be updated by the addition of an amount dependent upon the product of the speed of the rotor and the time between the change in Hall effect sensor output event and the next update of the scaled output shaft position value. This allows the method to take into account movement of the rotor during this time interval. A motor rotor speed sensor may be provided. Most preferably, the rotor speed could be calculated from a speed sensor on the output shaft combined with a knowledge of gearbox ratio. The speed sensor may form part of a combined speed/torque/position sensor.

The method may further comprise estimating a separate offset value for each direction of rotation of the rotor. This is advantageous in that it

allows the effect of differing properties of the system in different rotational directions to be taken into account.

When a clutch is provided as a part of the intermediate means, the relationship between scaled output shaft position value and rotor position value can not be determined whilst the clutch is dis-engaged. In this state, the method is invalid and so a further step of determining the state of the clutch can be included. When the clutch is disengaged, a 'method valid' flag can be lowered so that the results of the method are ignored. Similarly, the 'method valid' flag can be raised when the clutch is engaged.

The offset may be further refined by incorporating an adjustment value dependent on the backlash present between the rotor and the output shaft. The backlash adjustment value can be estimated from the difference between the offset values for each direction of rotation. The offset may be further refined by incorporating an adjustment value dependent on the compliance of the gearset between the rotor and the output shaft. The compliance may be estimated, and may be a fixed pre-set value.

Additionally, that part of the offset due to torsion in the intermediate means due to motor output torque may be subtracted.

In order to estimate the backlash from the offset values, a filter can be employed to obtain the estimated backlash values. As the backlash value would not be expected to change rapidly, the filter may only be updated when either of the offset values for the forward or reverse direction have been updated.

The backlash value may be averaged over time to produce a backlash value which varies over time at a slower rate than the pre-averaged backlash value. This averaged value may then be used in all calculations. The averaging may be performed by passing the backlash value through a recursive filter.

At each initialisation of the system, the previously calculated value of backlash may be re-used. Thus, the method may comprise a further step of storing the backlash estimates when the system is powered down, for example by writing the value of the backlash estimate(s) into non-volatile memory on power down and reading the value(s) on power up.

In accordance with a second aspect, we provide an electrical power assisted steering system comprising:

an electric motor comprising at least a stator and a rotor, an output shaft connected to the rotor through an intermediate means,
a first sensing means at the motor adapted to produce an output indicative of the position of the rotor,
a second sensing means at the output shaft adapted to provide at least an output indicative of the position of the output shaft, and
an electronic processing means adapted to receive the first and second output signals and produce an estimate of the position of the rotor in accordance with the method of the first aspect of the invention.

Preferably, the electronic processing means is further adapted to control the operation of the electric motor based upon the estimated position of the rotor.

The first sensing means may comprise a plurality of Hall effect sensors adapted to detect the passing of magnets on the motor rotor. The second sensing means may comprise a dedicated angular position sensor or a combined torque sensor and angular position sensor.

The system may further comprise a pulse generating means adapted to produce a clock signal. The electronic processing means may be adapted to sample the output of the second sensing means upon each clock signal.

The system may also include a clutch between the rotor and the gearbox, or the gearbox and the output shaft. A clutch status determining means may be provided to produce a "method valid" signal when the clutch is engaged.

It will be understood that the present invention enables a high resolution measurement of motor rotor position to be obtained by combining information from a sensor provided on an output shaft with information having low resolution but high accuracy from a sensor provided at the motor rotor. Specifically, the low resolution information can be employed to update an offset value which enables positional information obtained from the output shaft sensor to be correlated to the rotor position where an arbitrary relationship between the angular position of the output shaft and motor rotor exists. This is especially advantageous in a system in which a clutch is provided as a part of the intermediate means, and/or a system in which the output shaft position is measured with respect to an arbitrarily determined datum.

There will now be described, by way of example only, one embodiment of the present invention with reference to the accompanying drawings in which:

Figure 1 is an illustration of a system comprising an electric motor connected to an output shaft via an intermediate means;

Figure 2 is a table illustrating the motor rotor position corresponding to the commutator state codes generated by the Hall effect sensors;

Figure 3 is a flow diagram for a software routine embodying the method of the present invention;

Figure 4 illustrates the effect of backlash between the rotor and the output shaft plotted as backlash against motor current; and

Figure 5 is a flow diagram of an alternate embodiment of a software routine for calculating motor rotor position.

A system in accordance with the invention suitable for use with the method of the invention is illustrated in Figure 1 of the accompanying drawings.

A method in accordance with the invention is embodied in the form of a software algorithm, as shown in the block diagram of Figure 3. In the method, the torque sensor provides continuously sampled information 103 from Hall effect sensors which is used to ensure correlation between an output shaft angular position and the angular position of a rotor.

The system comprises an electric motor 1 connected to an output shaft 2 via a gearbox 3. The output shaft 2 carries a torque sensor 4 which is adapted to provide output signals: a torque value, an output speed

value 101 and a "measured output shaft position value "102 representative of the torque, speed and angular position of the output shaft respectively. The electric motor is provided with three serially arranged Hall effect sensors 5 which provide an output 103 in the form of a three-bit digital code. Each combination of digits defines a range of positions for the motor rotor, with the digits changing from one combination to another at predetermined rotor positions as the rotor magnets pass the Hall sensors. These change points may correspond to a commutation point. For three sensors, each digit combination corresponds to a range of rotor positions of 60° as six different codes are possible. This is shown in Figure 2.

The Hall sensors only provide accurate position information at the instant at which the Hall sensor output code changes. At all other rotor positions the Hall sensors can only state whether the rotor is within a particular 60 degree electrical range (for 3 sensors). The motor position value produced by the Hall effect sensors is stored 104 as a "measured absolute position value". To improve on this resolution, the method of the present invention employs output shaft position information from the torque sensor 4.

The presence of the gearbox 3 between the rotor and the output shaft 2 means that in order to calculate the angular position of the motor from a measurement of the output shaft position, the "measured output shaft position value" must first be multiplied by the gearbox ratio to produce a scaled output shaft position value which maps correctly onto the rotor shaft position. This is calculated 111 as follows:

scaled output shaft position value = (measured output shaft position value x motor

output shaft ratio) mod 360°

where motor output shaft ratio = gearbox ratio x half number of rotor poles.

The inclusion of "mod 360" indicates the use of modulo -360° arithmetic. For example, under this arithmetic, -10° → 350°, 380° → 20°, 360° → 0° etc.

The inclusion of "half number of rotor poles" converts the position value into electrical motor position rather than mechanical angular position.

The above equations map the position information from the output shaft onto the rotor taking into account the gearbox ratios. However, they do not take into account any offset present. In a practical system of the kind shown in figure 1, there is an arbitrary relationship between the" "scaled output shaft position value" (in the range 0-360°) and the position of the rotor (in the range of 0-360°). Thus, in order to utilise information regarding the position of the output shaft to determine the position of the rotor, the offset between the rotor and the output shaft must be known. In order to eliminate the effect of the offset, the following calculation 105 is used:

alignment offset value = measured absolute motor position value - scaled output shaft position value.

The value of "measured absolute motor position value" is obtained from the Hall effect sensors output codes and will change as the motor rotates. Only the value at the instant of a change in output code is of high

accuracy. The above equation therefore generates an offset value which is representative of the angular offset between the actual motor rotor position value and the scaled output shaft position value. The equation is only valid if the measured absolute motor position value and the scaled output shaft value are obtained at the same instant. In practice, however, this may not be possible. In the embodiment described herein, the output shaft position value from the torque sensor is measured at regular time intervals using a clock signal to trigger a sample of the value. However, a change in Hall sensor code only occurs at indeterminate times and will probably not coincide exactly with a clock pulse. To get round this problem, the measured absolute motor position value is corrected using the following equation:

corrected absolute motor position value = measured absolute motor position value + (motor velocity x time since last change in value of measured absolute motor position value).

The "corrected absolute motor position value" can then be substituted for the measured value in calculating the alignment offset value. This ensures that the distance travelled by the motor during the time interval between a commutation event and the update of the offset is taken into consideration, and eliminates the need to obtain simultaneous measurements of output position when a commutation event occurs. In a system where the output shaft position value is measured on each clock pulse, this interval will correspond to the time from a commutation event to the next clock pulse.

In addition to the above method steps which enable the offset to be calculated and updated, an alignment offset is required for each motor

direction. Thus, the software calculates alignment offset values in each motor direction (forward and reverse) and stores two separate values. These two offsets are filtered to prevent sudden changes to the motor position. The filters may be simple slew rate limits or recursive filters, and the following software algorithm 105 is used:

```
IF        (motor current > 0) THEN
          filtered forward alignment offset = FILTER
                                              (alignment offset
                                               value)
ELSE IF   (motor current < 0) THEN
          filtered reverse alignment offset = FILTER
                                              (alignment offset
                                               value)
```

The resolution of the two filtered offset values should ideally be better than that of the unfiltered offset value.

Having obtained the forward and backward alignment offset values, the final motor alignment offset is calculated 107 as follows:

final motor alignment offset value = (filtered forward offset value + filtered reverse offset value) $\div$ 2

In addition to providing an updated value of alignment offset using Hall sensor information in combination with the output shaft position information, the two filtered offset values are used to calculate 110 a

measure of the backlash present between the rotor and the output shaft as follows:

Estimated gearbox backlash magnitude = FILTER (filtered forward alignment offset - filtered reverse alignment offset) ÷ 2

Again, a filter 109 is employed to ensure the backlash estimate does not change rapidly, and in practice only a gradual change in the backlash magnitude should occur.

The backlash correction factor is dependent upon the motor current, i.e. upon the motor output torque. The characteristic will always be symmetrical about zero current and can be defined by a hysteresis gain value and a half width value. Figure 4 is a plot of backlash against motor current with the gain 21 and half width 22 marked on.

Having calculated the scaled output shaft position value, the final motor offset value and the backlash correction value, the final estimated rotor position is calculated 108 using the expression:

Final estimated rotor position value = (scaled output shaft position value + motor offset + backlash value) mod 360°.

This value is valid provided that the motor rotor and output shaft are engaged. However, where a dis-engaged clutch is provided between motor and output shaft, the expression will be invalid. To overcome this possible problem, the software algorithm includes a step 106 of checking

clutch engagement, and it is notified that the clutch is disengaged, a "method valid" flag is lowered to warn that the equation is invalid. In that event, motor position can be easily estimated from the expression:

final estimated rotor position value = commutation centre position value (as shown in Figure 2)

The values of final estimated rotor position and motor rotor speed can be used as control inputs for driving the electric motor. When the "method valid" flag is lowered, motor control is in accordance with a 'standard', commutated DC control. When the more accurate information from the output shaft sensor can be used, a more refined motor control algorithm can be used. For example, small variations in commutation point about the nominal commutation point can be effected.

A second control strategy is shown schematically in Figure 5.

In this embodiment, an output shaft velocity measurement is made which is initially rescaled by a known constant factor into motor electrical velocity units. An output shaft position measurement is similarly rescaled into motor electrical position units and extrapolated forward to the present time, using the motor velocity signal, so as to compensate for any staleness in the original measurement. An estimated alignment offset is added to re-reference the scaled output shaft position value with respect to the motor rotor. A combined gearset compensation signal is then added to compensate for any backlash and compliance.

The gearset compensation signal is made of two components: gearset torsion (i.e compliance) and backlash correction offset. Some gearsets have been found to have backlash that increases very slowly as the

gearteeth wear, but to have compliance that hardly varies at all over the life of an EPAS system. A prescribed gearset compliance is therefore multiplied by motor torque (which may be inferred from measurements of the motor current) to yield gearset torsion. The backlash correction offset depends on the motor torque and an estimate of the backlash magnitude derived in software to be described below.

The resulting motor electrical position signal can be used as a motor control feedback signal and allows a better quality of control to be established.

The motor electrical velocity and the motor torque can be employed to decide whether to update the gearset parameter estimates. The model is updated whenever the motor torque is consistent with the gearset being meshed and the motor speed is neither too fast nor too slow for accurate measurement.

When these conditions are met the signals from the motor rotor position sensors (usually binary state Hall effect probes) are first decoded and then corrected for measurement staleness. The difference between the motor electrical position signal and the corrected rotor position measurements is the error in the "motor offset" model. The model has two output parameters, the "estimated alignment offset" and the "estimated backlash magnitude". They are adjusted so as to keep the average motor offset model error close to zero.

The estimated backlash magnitude is derived by low pass filtering the difference between two position offsets, the forward and the reverse. The forward offset is adjusted to keep the average motor offset model error close to zero when the motor torque is positive and the reverse when it is

negative. The two offsets are thus adjusted to account for the average column/motor discrepancy when either one face of the gearset is in mesh, or the other. The difference between the two offsets may increase slightly over the life of the system as the faces of the gearset wear. The backlash magnitude parameter may be compared with a threshold value so as to indicate unacceptable wear as in the first embodiment. Since the backlash magnitude will vary only very slowly it may be stored in non-volatile memory (NVM) at the end of each period of operation. The low-pass filter can be re-initialised to the NVM value when operation re-starts, for example in an electric power steering system this may be at the start of each journey.

The estimated alignment offset may be calculated from slew-rate limiting the mid-point of the two position offsets. Since the column position is usually referenced to an entirely arbitrary datum (such as the power-up value) the mid-point of the two position offsets is also entirely arbitrary at start-up and no benefit arises from storing an averaged value in NVM. Instead the slew rate filter can be re-started from the first position offset measurement.

The control strategy is described in more detail in the following description which outlines the various steps embodied in the schematic of Figure 5.

Firstly the control strategy calculates or obtains values of output shaft velocity 202 and absolute output shaft position 203 using a column sensor (i.e. a combined torque and position sensor) 201.

Next, using a preset value of gearbox ratio 204 as for the first embodiment, the values 202, 203 are multiplied by the gearbox ratio to

produce a motor electrical velocity value 205 and a corrected scaled output shaft position value 206 according to:

corrected scaled output shaft position value = [(measured output shaft position value x motor box output shaft ratio) + (motor velocity x time since last measurement of absolute output shaft position value)] mod 360°

Motor electrical velocity = (measured output shaft velocity x motor output shaft ratio)

The corrected scaled output shaft position value this incorporates a correction for movement of the rotor between changes in the value of output shaft position. This is different from the first embodiment where no such correction was performed. Of course, the first embodiment could be modified to make such a correction.

From the value of corrected scaled output shaft position, an "aligned motor electrical position" value can be calculated as follows:

aligned motor electrical position = MOD 360 (corrected scaled output shaft position + estimated alignment offset)

The "estimated alignment offset" is an output value representing the error due to differences between the datum points about which the measurements of output shaft position and motor rotor position are made, and is calculated in a manner described herein after. The aligned motor electrical position thus compensates for the effects of such .datum misalignment

As stated previously, compensation for the effect of the gearset is required. This error component is made up from two components: effect of compliance and effect of backlash. Some practical gearsets have been found to have backlash that increases very slowly as the gearset teeth wear, but to have compliance that hardly varies at all over the life of the system. Accordingly, it is possible to use a prescribed value of gearset compliance 208 (for example stored in a non-volatile memory) which can be multiplied by a value of the motor torque 207 to yield a gearset torsion value 209 such that:

gearset torsion = gearbox compliance x motor torque.

The motor torque value may be measured or inferred.

Whilst a predetermined value of compliance can be used successfully, a calculated value of backlash is desirable to take into account changes due to wear of the teeth.

The method of Figure 5 incorporates a backlash correction algorithm which generates a "backlash correction offset value" 211 that is dependent on the motor torque using a gearset model 210.

The characteristics of the plot of backlash against motor current will always be symmetrical about zero and shall be defined by the

BACKLASH CORRECTION HYSTERESIS GAIN and the BACKLASH CORRECTION HALF WIDTH, as shown in Figure 4.

The value of backlash correction offset 211 may be bounded so that its magnitude does not exceed the estimated backlash magnitude ÷ 2. These calculations are made at every iteration, as follows:

IF BACKLASH CORRECTION HYSTERESIS GAIN*
(motor torque-BACKLASH CORRECTION HYSTERESIS HALF WIDTH) >
old backlash correction offset
THEN backlash correction offset = BACKLASH CORRECTION HYSTERESIS GAIN* (motor torque-BACKLASH CORRECTION HYSTERESIS HALF WIDTH)

ELSE IF BACKLASH CORRECTION HYSTERESIS GAIN*
(motor torque + BACKLASH CORRECTION HYSTERESIS HALF WIDTH) <
old backlash correction offset
THEN backlash correction offset = BACKLASH CORRECTION HYSTERESIS GAIN* (motor torque + BACKLASH CORRECTION HYSTERESIS HALF WIDTH)

ELSE
backlash correction offset = old backlash correction offset
END
backlash correction offset =
MIN (
MAX (backlash correction offset, -estimated backlash magnitude/2),
+ estimated backlash magnitude/2)

old backlash correction offset = backlash correction offset

Where MIN(x,y,z) is the algebraic minimum of x,y,z

and MAX(x,y,z) is the algebraic maximum of x,y,z.

The gearset torsion 209 and "backlash correction offset" 211 can then be combined to produce a "gear wear effect value" 212 which may be combined with the value of aligned motor position to produce a "final estimated motor rotor position value" 213 such that:

Final estimated motor rotor position value = MOD 360 (aligned motor electrical position + combined gear wear effect)

where:

combined gear wear effect = backlash correction offset + gearset torsion.

Alternatively, at power up, or perhaps when the above would produce an unreliable result, the following can be used:

Final estimated motor rotor position = commutation centre position.

An additional function may be provided which is adapted to continuously detect when the gearbox is fully meshed (i.e does not lie in the backlash region). The relationship between the motor position and the column position can then be used to update the motor offset model.

A minimum velocity threshold may also be imposed which is set high enough to avoid updating the absolute motor position and the gearset model from a Hall sensor transition which is "too old".

The gearbox fully meshed flag can be set to indicate that the gearbox is fully meshed whenever the following conditions are all met:

ABS (motor electrical velocity) > MOTOR MESH MIN VELOCITY THRESHOLD

ABS (motor electrical velocity) < MOTOR MESH MAX VELOCITY THRESHOLD

ABS (motor torque) > MOTOR MESH MIN TORQUE THRESHOLD

SIGN (motor torque) = SIGN (motor electrical velocity)

The flag can be reset if any of the above conditions do not hold.

The method of calculating the estimated alignment offset will now be described.

In a first stage of the gearset model 210, the "motor electrical velocity" 205 is combined 220 with a "measured absolute motor position value" 230 obtained from position sensors in order to produce a corrected absolute motor position value 240 which is compensated for the time elapsed since the measurements were made such that:

corrected absolute motor position = MOD 360 (measured absolute motor position value + [motor electrical velocity x (time now-time of measurement)])

Thus, where a Hall effect sensor is used to measure absolute motor position, this algorithm compensates for movement of the motor after a change in Hall effect sensor state to increase accuracy.

The value of "corrected absolute motor position" 240 is combined with the value of final estimated motor rotor position 213 to produce a "motor offset model error" value 250 given by:

motor offset model error = MOD 360 (corrected absolute motor position-Final estimated motor rotor position + 180°) -180°

This signed expression is the shortest angular distance from the motor electrical position to the absolute motor position in either direction around the circle and hence constrains the motor offset model error to lie within -180° to + 180°). If, during a journey, corrected absolute motor position consistently leads measured motor absolute position by, say, 10° when driving in a positive direction, then this expression will produce a consistent + 10° result even when corrected absolute motor position wraps round from 360° to 0° while measured absolute motor electrical position is still climbing from 350° towards 360°. The "motor offset model error" is equally likely to be positive as negative irrespective of the motor drive direction.

Having calculated the "motor offset model error" 250, a motor position offset is calculated for each direction of drive , forward 260 and reverse 270. Each of these "motor position offsets" is individually urged by integral action towards a target value (unknown at the start of a journey) that will yield a low motor offset model error. The generation of these offsets from an error signal with a low average value requires

substantial DC gain (e.g. integral action) to reveal the difference in the relative positions of, for example, a worm and (scaled) wormwheel in the gearbox during forward and reverse drive.

One of the two offset values can be updated according to the direction of motor torque:-

IF (motor torque > 0) THEN

forward motor position offset = (forward motor position offset + motor offset model error * motor position offset error gain)

ELSE

reverse motor position offset = (reverse motor position offset + motor offset model error * motor position offset error gain)

ENDIF

The forward and reverse motor position offset values can both be initialised when the first motor offset model error 250 is calculated. A "motor offsets initialised flag" can then be set to indicate that the motor offset model error 250 is now valid. The offset values can be initialised according to the direction of motor torque:

IF (motor torque > 0) THEN

forward motor position offset = corrected absolute motor position-corrected scaled output shaft position-gearset torsion

reverse motor position offset = forward motor position offset-estimated backlash magnitude

ELSE

reverse motor position offset = corrected absolute motor position-corrected scaled output shaft position-gearset torsion

forward motor position offset = reverse motor position offset + estimated backlash magnitude

ENDIF

The two values (forward and reverse) of motor position offset 260, 270 can then be combined to produce an estimate of the backlash magnitude 280 and an estimate of the alignment offset 290.

The backlash magnitude 280 can be estimated from the difference between these two motor position offsets 260 and 270:

measured backlash magnitude = min (max (forward motor position offset-reverse motor position offset, 0°), MAX ESTIMATED BACKLASH)

estimated backlash magnitude= [measured backlash magnitude+ (backlash filter constant-1) * estimated backlash magnitude] / backlash filter constant

The estimated backlash magnitude can be restored from non-volatile memory (NVM) at the beginning of each journey and stored back to NVM at power-down. A further filter shall be applied when storing the estimated backlash magnitude to NVM to prevent somewhat erroneous data gathered during a short journey from having a long-term affect on the system performance. This filter shall limit the change to a maximum of ± NVM BACKLASH MAX CHANGE per power cycle.

The backlash magnitude estimate 280 is used to calculate a backlash correction offset value 300 which can be combined 301 with the gearset torsion value 209 to yield the value of combined gear wear effect 212

which is added 302 to the aligned motor electrical position value to yield the "final estimated motor rotor position" value 213 as described herein before.

The backlash correction algorithm therefore generates a position correction component that depends on the motor torque.

At the first ever system power-down during initial EPAS unit testing, the value of estimated backlash magnitude 280 can be stored in NVM without filtering.

Having calculated the forward and reverse offsets, the estimate of the alignment offset 290 can be calculated. The value can be constantly updated towards the mid-point of the two motor position offsets:-

measured alignment offset = (reverse motor position offset + forward motor position offset) ÷ 2

alignment offset change = measured alignment offset-estimated alignment offset

alignment offset change = min (
max (alignment offset change, -ALIGNMENT OFFSET MAX CHANGE),
+ ALIGNMENT OFFSET MAX CHANGE)

estimated alignment offset = estimated alignment offset + alignment offset change.

On initialisation, the following estimate of alignment offset can be used:

estimated alignment offset = (reverse motor position offset + forward motor position offset) ÷ 2

Thus, it will be readily understood by the man skilled in the art that the second embodiment provides a method of calculating the position of a

rotor in a motor at a moment in time taking into account the effects of backlash and compliance. The second embodiment is capable of resetting the backlash estimates employed to compensate for wear of the system over time. It will also be understood that many of the refinements described in relation to the first aspect are applicable to the second aspect. For example, the arrangement and location of sensors may be the same.

It will also be understood that the second embodiment employs the same output measurement signals of motor position, output shaft position and torque acts as the first embodiment, but provides an improved method of calculating absolute motor position by making assumptions about compliance in the system.

CLAIMS

1. A method of calculating the position at a moment in time of a rotor in a motor 1 which is connected to an output shaft (2) through an intermediate means (3) characterised by the steps of:

obtaining a measured rotor position first value indicative of the angular position of the rotor at a first instance in time using a first sensing means provided at the motor;

measuring an output shaft position second value indicative of the angular position of the output shaft at a second instance in time using a second sensing means (4) provided on the output shaft (2); and

combining said first and second values to produce an estimate of the angular position of the rotor at said moment in time.

2. A method according to claim 1 characterised in that the intermediate means comprises a gearbox (3) and by including the further step of multiplying the measured second value by at least the gearing ratio of the gearbox to produce a scaled output shaft position value.

3. A method according to claim 2 characterised by the further step of calculating an offset value indicative of the offset between the actual position of the rotor and the position of the rotor as given by the scaled output shaft position value.

4. A method according to claim 3 characterised in that the offset value is calculated by comparing the measured rotor position first value with the scaled output shaft position value.

5. A method according to any one of claims 3 or 4 characterised in that a corrected offset value is calculated by combining the offset value

with an amount equal to the product of the motor rotor velocity and the time between obtaining the measured rotor position first value and the output shaft position second value.

6. A method according to any one of claims 3 to 5 in which a forward offset value and a reverse offset value are calculated dependent upon the sense of the motor output torque.

7. A method according to any preceding claim characterised by the further step of calculating a backlash value indicative of the backlash between the rotor and the output shaft.

8. A method according to claim 7 characterised in that the backlash value is averaged over time to produce a backlash value which varies over time at a slower rate than the pre-averaged backlash value.

9. A method according to claim 8 characterised in that the backlash value is averaged by passing through a recursive filter.

10. A method according to any one of claims 3 to 9 which is characterised by the further step of subtracting that part of the offset which is dependent upon torsion caused by motor output torque in the intermediate means.

11. A method according to claim 10 as dependent upon claim 5 characterised in that the offset and backlash values are combined with the scaled rotor position value to produce an estimated rotor position value indicative of the absolute position of the rotor.

12. A method according to any one of claims 3 to 11 characterised in that the offset value is recalculated whenever the measured rotor position first value changes.

13. A method according to any preceding claim characterised in that the measured output shaft position second value is obtained by sampling the output of the second sensing means in response to a clock signal.

14. A method according to any preceding claim characterised in that the measured rotor position first value is obtained by measuring the output of a plurality of Hall effect sensors.

15. An electric power assisted steering system comprising:

an electric motor (1) comprising at least a stator and a rotor, an output shaft (2) connected to the rotor through an intermediate means (3), a first sensing means (5) at the motor (1) adapted to produce an output indicative of the position of the rotor, and a second sensing means (4) at the output shaft (2) adapted to provide at least an output indicative of the position of the output shaft, and characterised by an electronic processing means (6) adapted to receive the first and second output signals and produce an estimate of the position of the rotor in accordance with the method of any one of claims 1 to 14.

16. Apparatus according to claim 15 characterised in that the electronic processing means is further adapted to control the operation of the electric motor based upon the estimated position of the rotor.

17. Apparatus according to claim 15 or 16 characterised in that the first sensing means comprises a plurality of Hall effect sensors adapted to detect the passing of magnets on the motor rotor.

18. Apparatus according to claim 15, 16 or 17 characterised in that the second sensing means comprises a dedicated angular position sensor or combined torque sensor and angular position sensor.

19. Apparatus according to any one of claims 15 to 18 characterised by further comprising a pulse generating means adapted to produce a clock signal, and the electronic processing means is adapted to sample the output of the second sensing means upon each clock signal.

20. Apparatus according to any one of claims 15 to 18 which is characterised by further including a clutch between the rotor and the gearbox, or the gearbox and the output shaft, and clutch status determining means adapted to produce a "method valid" signal when the clutch is engaged and/or a "method invalid" signal when it is dis-engaged.

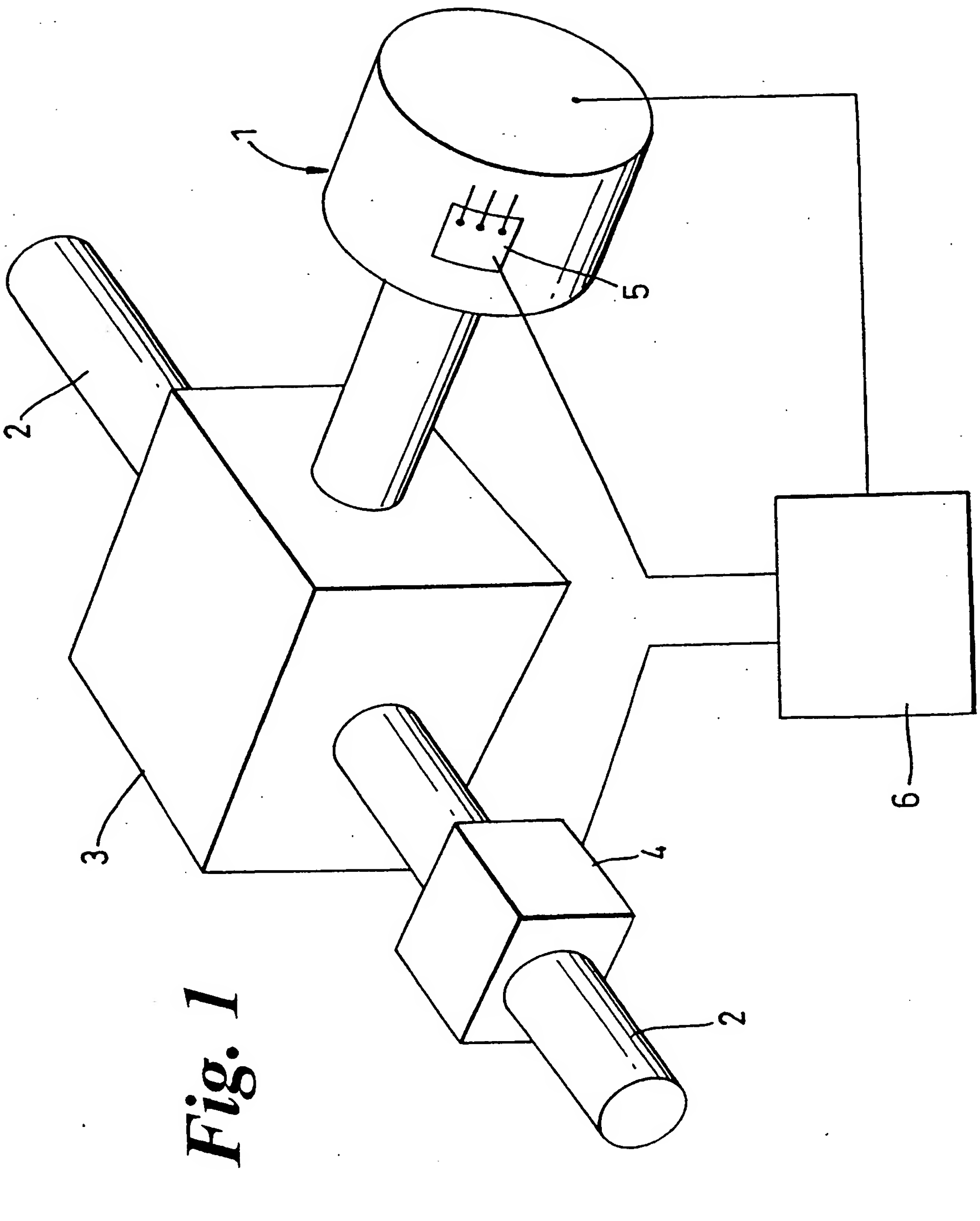

Fig. 1

SUBSTITUTE SHEET (rule 26)

HALL_C	HALL_B	HALL_A	motor commutation state	commutation centre position	rotor position range
0	1	1	3	0°	330° 30°
0	0	1	1	60°	30° 90°
1	0	1	5	120°	90° 150°
1	0	0	4	180°	150° 210°
1	1	0	6	240°	210° 270°
0	1	0	2	300	270 330
0	0	0	0(Invalid)	–	
1	1	1	7(Invalid)	–	

Fig. 2

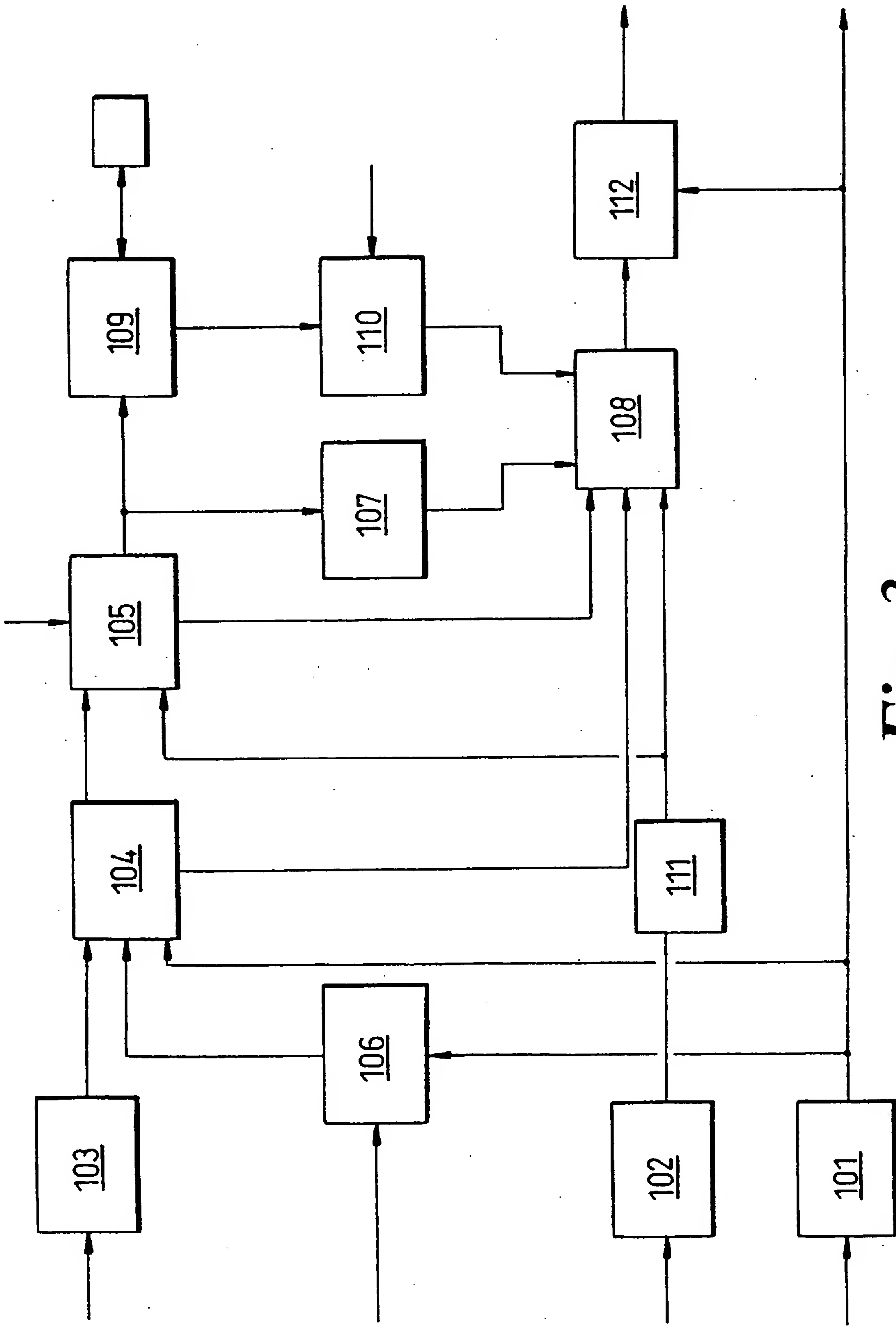

Fig. 3

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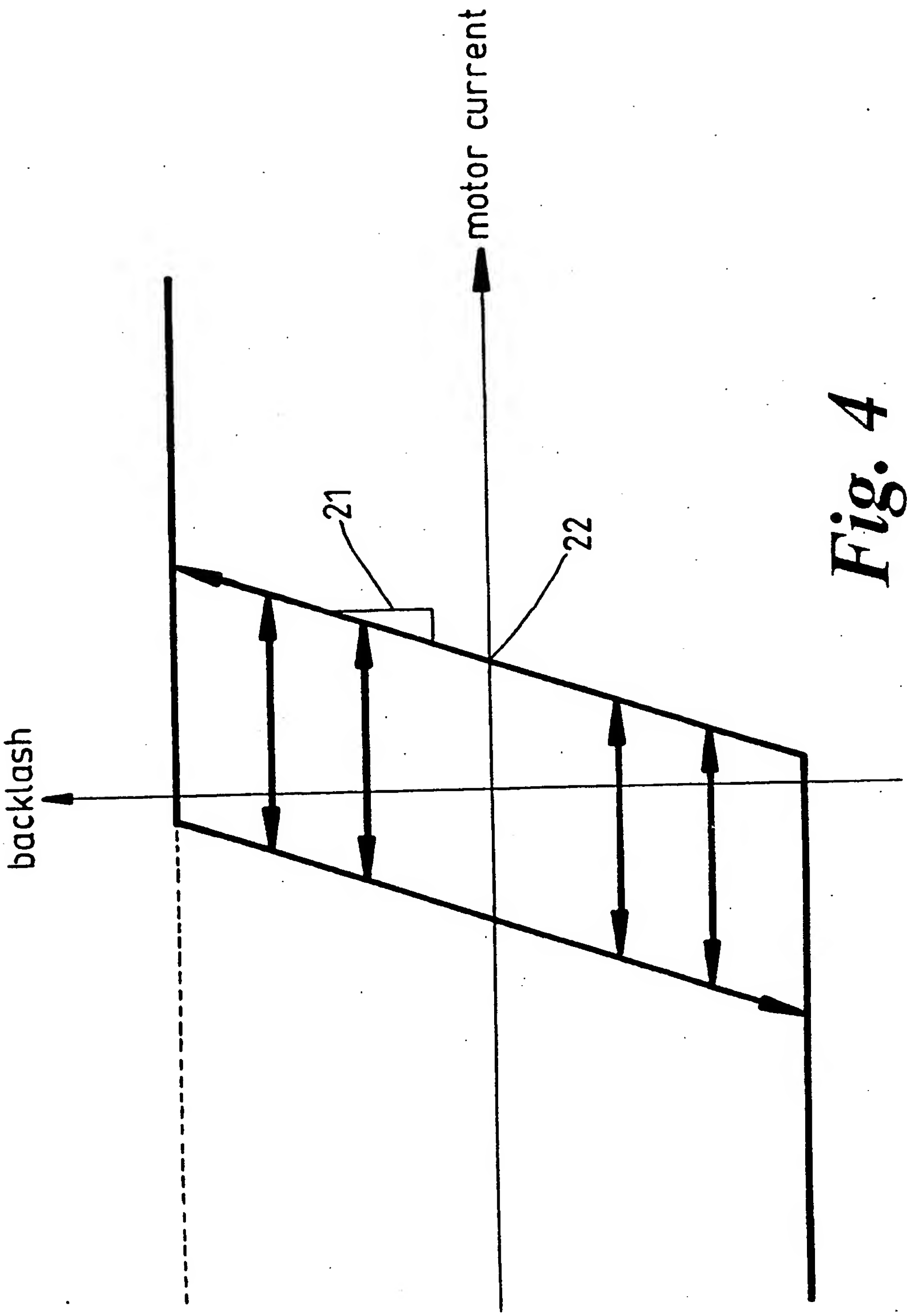

Fig. 4

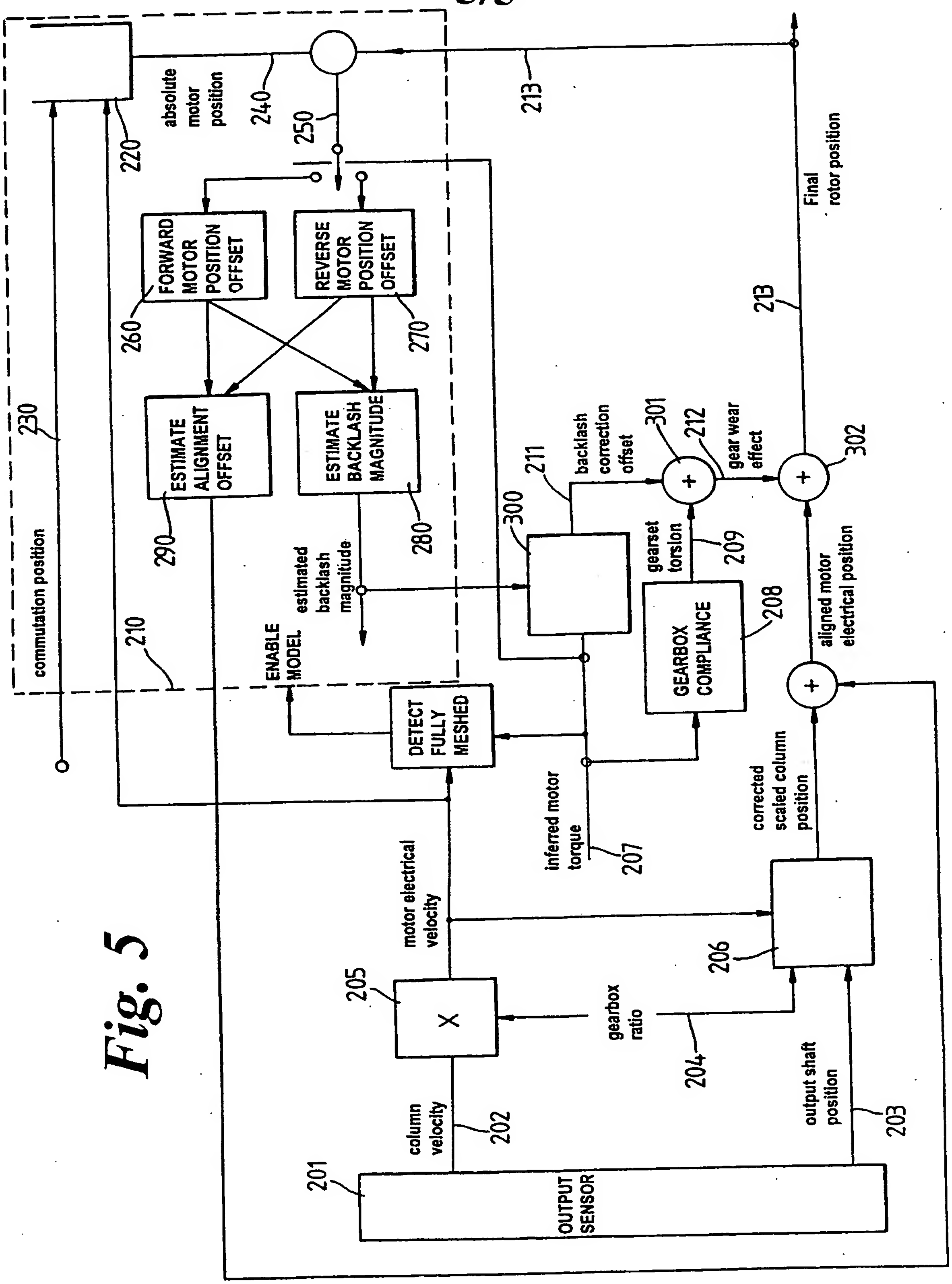
absolute motor position
240
250
213
220
FORWARD MOTOR POSITION OFFSET
REVERSE MOTOR POSITION OFFSET
260
270
Final rotor position
213
230
ESTIMATE ALIGNMENT OFFSET
ESTIMATE BACKLASH MAGNITUDE
290
280
commutation position
210
ENABLE MODEL
estimated backlash magnitude
300
211
backlash correction offset
301
212
gear wear effect
302
gearset torsion
209
GEARBOX COMPLIANCE
208
aligned motor electrical position
DETECT FULLY MESHED
inferred motor torque
207
corrected scaled column position
motor electrical velocity
205
X
gearbox ratio
204
206
column velocity
202
output shaft position
203
201
OUTPUT SENSOR

Fig. 5

INTERNATIONAL SEARCH REPORT

Intern ial Application No
PCT/GB 98/02338

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H02P6/16 B62D5/04 G05B19/401

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H02P B62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 25767 A (LUCAS IND PLC ;COLES JEFFREY RONALD (GB); JONES RUSSELL WILSON (GB) 17 July 1997 see page 8, line 13 - page 10, line 2 see page 18, line 21 - page 19, line 4 see page 25, line 4 - page 26, line 8 see claims 13-18 see figure 13	1,15-18
A		2-14,19, 20

X	PATENT ABSTRACTS OF JAPAN vol. 009, no. 189 (E-333), 6 August 1985 & JP 60 055880 A (TOSHIBA KIKAI KK), 1 April 1985 see abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 December 1998	11/12/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Chapple, I

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Internal Application No
PCT/GB 98/02338

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9725767 A	17-07-1997	AU 1389197 A	01-08-1997
		EP 0873587 A	28-10-1998

Form PCT/ISA/210 (patent family annex) (July 1992)